PETROLOGICAL STUDIES IN THE ORDOVICIAN OF NEW SOUTH WALES. I.

THE COOMA COMPLEX.*

By Germaine A. Joplin, B.Sc., Ph.D., Linnean Macleay Fellow of the Society in Geology.

(Plate v; eleven Text-figures.)

[Read 17th June, 1942.]

Contents.

I. *Introduction.*

Cooma, situated on the Southern Tablelands of New South Wales at a distance of 268 miles by rail from Sydney, presents an interesting problem in metamorphic geology.

The general geology of the area was investigated by W. R. Browne in 1914 and the age of the igneous rocks was further discussed by him in 1929. Slates containing Upper Ordovician graptolites have been invaded by bathyliths of Ordovician, of Silurian and of Kanimbla (Devonian or Carboniferous) age. To the east of Cooma the Ordovician rocks are overlain by Silurian strata, and much of the area, particularly that to the south, is covered by Tertiary basalt.

The present work is a petrological study of the Ordovician granite-gneiss and of the Ordovician country-rocks unaffected by the Silurian intrusions and locally altered by the Kanimbla granite. The first aim of the investigation was to identify the original country-rocks prior to their metamorphism and to trace each rock-type through the various grades of metamorphism.

The map of the district (Plate v) is a reproduction of that published by Browne (1914) with some modifications and additions both by Dr. Browne and myself. The original survey extended south to a latitude just beyond Arable Trigonometrical Station, and I have continued mapping a further six miles. In this southerly extension, however, boundaries are only sketched as the detailed mapping of granite and basalt has little bearing on the present problem. Specimens of schist and of granitized schist, however, have been carefully collected and their exact positions plotted on the map, and it is from a microscope examination of these specimens that the various metamorphic zones have been drawn (Plate v).

---

* An earlier contribution by the writer, dealing with metamorphism and assimilation in the Cooma district, was published in the *Journal and Proceedings of the Royal Society of N.S.W.*, 73, 1939, 86-106.

II. Nature of the Country-Rocks and Distribution of the Metamorphic Zones.

For the purpose of the present paper the Ordovician rocks have been subdivided into the Coolringdon and Binjura Beds. The latter have been invaded first by several small ultrabasic and basic masses and then by the Cooma granite-gneiss. On account of the strong isoclinal folding, with its prevailing dip to the east, the frequent covering of basalt and the lack of exposures, it has not been possible to map any individual bed; and this adds to the difficulty of working out structures and thus determining the relative stratigraphical positions of the Coolringdon and Binjura Beds. As plutonic intrusions more commonly invade anticlinal structures rather than synclinal troughs, it is assumed that the Binjura Beds occur in an eroded anticline and that the Coolringdon Beds overlie them. The presence of such a folded structure is indicated by the occurrence of black slates of Coolringdon-type near Bunyan on the eastern side of the complex.

Owing to the difficulty of mapping individual beds, it has been found impossible to trace any single bed through the several metamorphic zones, and the identity of many of the country-rocks has been established mainly by chemical means. The various rock-types are listed in Table 1.

As pointed out by Browne (1914), a complete transition from graptolite-bearing Ordovician slate, through phyllites and schists into gneisses may be traced on a west-to-east traverse from Bridle Creek across Dairyman's Plain to Cooma Creek.

Reference to Plate v will show that it has been possible to map a number of metamorphic zones, but the junction between the Coolringdon and Binjura Beds, to the west of Cooma, is unfortunately almost coincident with the chlorite isograd, and thus no member of the Coolringdon Beds occurs within the chlorite-zone, and, with the exception of a few tuffaceous sandstones, no member of the Binjura Beds in a grade lower than the chlorite-zone. In the south-western part of the area the Coolringdon Beds have been invaded by a Devonian or Carboniferous granite and certain contact effects have been produced in the zone of clastic mica.

From west-to-east the Binjura Beds pass from the chlorite-zone into the biotite-zone, and at a distance of about 3¼ miles from the Cooma gneiss the biotite-schists are contact-altered, large crystals of andalusite being developed in rocks of suitable composition. This andalusite-zone passes imperceptibly inwards into a zone of sillimanite-bearing paragneisses and permeation-gneisses, which are indistinguishable in the field, and for the purposes of mapping, have been grouped as the permeation-zone. At a distance of 1½ to 2 miles from the Cooma gneiss the permeation-gneisses are injected by granitic and pegmatitic material and give place to injection-gneisses with typical *lit-par-lit* structure.

The injection-zone, the permeation-zone and the andalusite-zone are unquestionably related to the Cooma gneiss, the first two being granitized zones and the last the thermal aureole beyond the outer limit of granitization. The relation of the biotite and chlorite zones to the andalusite-zone, and hence to the granite-gneiss, is obscure. There is a general parallelism between the chlorite, biotite and andalusite isograds, but owing to the cover of Tertiary basalt in the south of the area, these isograds can be traced only for a limited distance, and much important evidence relating to the zones is possibly lacking.

The six metamorphic zones of Ordovician age have been plotted on the map (Plate v), as well as a contact-zone of much later date. The effect of each of these grades of metamorphism on the various types of country-rock is tabulated in Table 1.

III. Ungranitized Country-Rocks and their Metamorphism.

1. Field Relations.

On account of the difficulty of following individual beds, detailed mapping of the strata has not been attempted and the map (Plate v) is primarily one to show the metamorphic zones. It has not even been possible to sketch the exact boundary between the Coolringdon and Binjura Beds, but apparently it is almost coincident with the chlorite isograd.

TABLE 1.

Nature of the Original Rock.	Zone of Clastic Mica.	Contact-Aureole of the Berridale Granite.	Chlorite-Zone.	Biotite-Zone.	Andalusite-Zone.	Permeation-Zone.	Injection-Zone.
COOLRINGDON BEDS. Siliceous Shales.	Siliceous Slates.	Chiastolite-Slates.					
Sandstones.	Sandstones and Sandy Slates.	Quartzites and Quartz-Hornfelses.					
BINJURA BEDS. Tuffaceous Sandstones.	Tuffaceous Sandstones with detrital Hornblende.		Clinozoisite-Granulite.	Amphibole Granulites and Garnet-Amphibole-Granulites.	Pyroxene-Granulites.		
Aluminous Mudstones and Shales.			Chlorite-Sericite-Schists.	Biotite-Schists.	Andalusite-bearing Biotite-Schists.	Sillimanite-Gneisses and Permeation-Gneisses (Mottled Gneisses).	Sillimanite-bearing Injection-Gneisses.
Sandstones with varying amounts of argillaceous matrix.			Quartz-Sericite-Schists and Quartz-Chlorite-Sericite-Schists.	Quartz-Biotite-Schists.	Quartz-Granulites and Andalusite-bearing Types.	Granulites and Mottled Gneisses.	Acid Injection-Gneisses.
Banded Sandy Shales.			Banded Quartz-Chlorite-Sericite-Schists.	Banded Biotite-Schists.	Banded Granulites and Andalusite-Schists.	Corduroy Granulites and Mottled Gneiss.	Acid Injection-Gneiss.
Basalts or Dolerites							Hornblende-Pyroxene-Granulites.
ULTRABASIC AND BASIC INTRUSIONS. Ultrabasic Types (?)						Chlorite-Amphibolite.	Chlorite-Amphibolite.
Norites and Gabbros							Amphibolites and Silicified Amphibolites.

The siliceous slates of the Coolringdon Beds are intercalated with sandstones of varying texture and colour. The slates are usually black and carbonaceous and often contain graptolite remains. In the area mapped the contact-aureole of the Berridale granite lies wholly within the Coolringdon Beds.

In the Binjura Beds argillaceous and arenaceous types alternate in bands several feet in thickness or in seams only a fraction of an inch wide. The tuffaceous sandstones, which are occasionally found just above the chlorite isograd, and therefore high in the Binjura Beds, also occur at lower levels interbedded with the alternating argillaceous and arenaceous types. Their usual occurrence is lenticular, the lenses being a foot or so in thickness and up to 15 feet in length. The contact-aureole of the Cooma gneiss is confined to the Binjura Beds which thus form the sedimentary foundation of the granitized zones.

The general strike of the Ordovician rocks is a little west of north, and to some extent this direction is followed by the trend of the metamorphic zones. Thus the chlorite isograd appears from beneath basalt on the road about ¾ mile south-west of Bobundra Trig. Station and trends north to Ingram's Creek where it is lost beneath basalt for a distance of some 7½ miles. In the Parish of Jillamatong it crops out again for a short distance, then disappears beneath basalt for a further 8½ miles, and reappears to the east of, and almost parallel to, the Murrumbidgee River in the Parish of Murrumbucka. It has been traced north to the mouth of Bulga Creek—a total distance of 25 miles. Where it can be measured, the chlorite-zone appears to be about ¾ mile in width.

As it disappears beneath basalt in the southern part of the area, the biotite isograd can be traced only for a distance of 14 miles, but over this distance the outcrop is fairly continuous, and it is approximately parallel to the chlorite isograd. The width of the biotite-zone cannot be satisfactorily measured since it is transgressed on its eastern side by the andalusite-zone, which is part of the contact-zone of the Cooma gneiss at a distance of about 3¼ miles from the granite-gneiss.

Reference to the map (Plate v) will show that the andalusite-zone and the granitized zones immediately adjacent to the gneiss occasionally crop out as small inliers in the basalt area in the Parish of The Brothers, thus indicating a south-east trend for the gneiss and its contiguous zones. The limited exposure of the chlorite isograd in the Parish of Jillamatong shows much the same trend, and there seems to be some parallelism between the chlorite and biotite isograds and the zones which are unquestionably related to the intrusive Cooma gneiss.

2. NOMENCLATURE.

The occurrence at Cooma of highly siliceous rocks, often with a slaty cleavage, has led to an inquiry into the nomenclature of such types. In the field these rocks have the appearance of clay-slates and were at first mistaken for the low-grade equivalents of the aluminous schists found in the higher grades of metamorphism. Chemical analyses have been made of members of both rock-series (Tables 2 and 3), and the aluminous types obviously fall into the class of the normal pelites (Van Hise, 1904; Tilley, 1926*a*). The term *pelite* is derived from the Greek πῆλος variously translated as *mud*, *clay* or *ooze*, and whilst these imply a textural limitation, clay alone suggests a chemical one.

In the current literature the term *pelite* is used very loosely, and there appears to be a tacit understanding that all pelites are clay-rocks with a characteristically high percentage of alumina—rocks that, in the higher grades of metamorphism, develop such minerals as almandine, cyanite and sillimanite. The normal pelite certainly has this composition, for it is probable that most normal mud-deposits contain an abundance of clay, which is characterized chemically by the presence of hydrous aluminium silicates (Holmes, 1920, p. 61). Other mud-deposits, however, may consist of finely-divided siliceous material or of volcanic dust, and the composition of the resultant pelite must vary accordingly (Hutchings, 1892; Holmes, 1920, p. 178).

To test the validity of these statements, a series of about two hundred chemical analyses of shales and clay-slates was examined (Clarke, 1926; Barth, 1936; Geological Survey Publications of Great Britain, U.S.A., Victoria and N.S.W.). It was found that the percentage of silica in these analyses varied from 45–85. The majority of the rocks fell in between 55% and 68% of silica, which is the range of the normal pelites, but those outside these limits appear to have been named according to their grainsize and general appearance in the field, without reference to their chemical composition.

Van Hise (1904) distinguishes three types of *psammite* (*sand-rock*); a division based on the nature of the constituent fragments and therefore indirectly on the chemical composition. He regards the *pelites* (*mud-rocks*), however, as a single group—the muds, and chemical differences are not recognized. In defining the various types of fragmental rock, Van Hise applies the term either to the sedimentary type or to its metamorphic equivalent. Tyrrell (1921), on the other hand, would apply the terms *pelite* and *psammite* only to metamorphic rocks.

In tracing a rock-type through several stages of metamorphism, it is convenient to use a term that can be applied either to the original sedimentary rock or to any of its metamorphic equivalents. The terms *arenaceous* and *argillaceous* are commonly used only for sedimentary rocks, and as no completely unaltered sedimentary types occur at Cooma, it is preferable to use the terms *psammite* and *pelite* in the wide sense of Van Hise to mean sand-rocks and mud-rocks respectively, whatever their metamorphic grade.

In view of the outstanding chemical differences among the pelites, it is desirable that some adjective indicating the chemical peculiarity of the original mud should be employed, and for the purpose of the present paper it is proposed to use the terms *siliceous pelite* and *aluminous pelite*, the latter being what is sometimes called the normal pelite (Tilley, 1926*a*) or more commonly merely pelite (Tilley, 1926*b*; Harker, 1932; Read, 1925, 1930, 1940; Barth, 1937).

The term *psammopelite* is applied here to a group of rocks which consisted originally of sand and mud either in a homogeneous mixture or in alternating layers. Although a definite chemical composition is implied by Tilley (1925) in describing the North-East Highland psammopelites, the term is used in the present paper only in a textural sense, the Cooma psammopelites differing widely in chemical composition according to the variety and proportion of admixed psammite and pelite.

3. COOLRINGDON BEDS.

(1) *Zone of Clastic Mica.*

(i) *Psammites.*

In the handspecimen these rocks vary a good deal in texture and colour, ranging from fine-grained quartzites to medium-grained sandstones which may be red, white, buff, grey or black. They are sometimes banded with finer seams of siliceous pelite, and could in this case be called banded psammopelites. Negative crystals of pyrites sometimes show on weathered surfaces.

Under the microscope these rocks have a clastic structure (Fig. 1A) with rounded or sub-angular grains of quartz and usually some felspar. Clastic mica may occur in single small greenish-brown flakes or in groups of small flakes. Grains of iron ore and detrital tourmaline also occur. The matrix is usually micaceous and may be strongly coloured by oxides of iron or by carbonaceous material. The felspar, though sometimes sericitized, is usually fresh oligioclase-andesine ($Ab_{70}An_{30}$–$Ab_{68}An_{32}$). The larger quartz grains often show cataclastic structure. Undulose extinction and granulation are common and sometimes a border of secondary quartz is developed. In a few of the more altered types the clastic quartz grains are slightly elongated and lines of secondary fluid-pores are at right angles to this elongation.

(ii) *Siliceous Pelites.*

These rocks are very abundant in the Coolringdon Beds, where they are intercalated with the psammitic types. In the handspecimen they are buff, grey or black finely-laminated rocks without sheen. A cleavage is sometimes developed, and the uncleaved more massive rocks have a slightly conchoidal fracture. On Ingram's, Cottage and Wambrook Creeks and at McCarthy's Crossing on Bridle Creek these rocks contain graptolites, and graptolites together with crystals of chiastolite are found in a contact-altered type near Berridale.

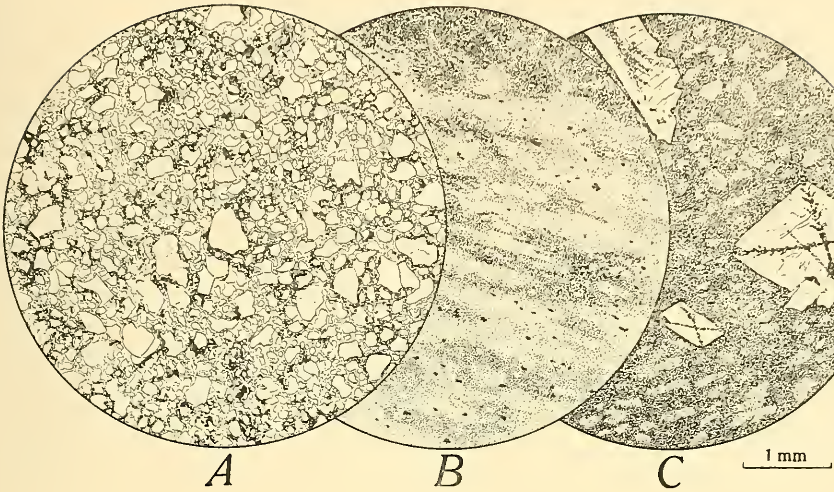

Fig. 1.

A. Low-grade psammite in Coolringdon Beds on Berridale Road, near Slack's Creek. The rock shows rounded and subangular grains of quartz in an argillaceous and ferruginous matrix. Note small patches of clastic mica. × 12.

B. Siliceous slate with carbonaceous bands from Wambrook Creek at crossing of Adaminaby Road. Note tiny clastic grains of quartz and iron ore. × 12.

C. Chiastolite-slate, Gygederick Hill near Berridale. Former slight schistosity indicated by orientation of incipient cordierite crystals. The groundmass consists mainly of finely-divided carbonaceous material and quartz. × 12.

TABLE 2.

	I.	II.	III.	IV.
SiO_2	85·96	80·37	78·45	79·25
Al_2O_3	8·49	10·04	12·92	11·86
Fe_2O_3 ..	0·33	0·35	1·48	0·86
FeO	0·19	1·44	0·95	0·81
MgO	0·65	0·57	0·36	1·28
CaO	0·10	0·37	0·19	0·17
Na_2O	0·48	0·93	0·23	1·08
K_2O	1·91	2·09	2·39	2·33
H_2O+ ..	1·37	2·44	2·32	1·30
H_2O- ..	0·07	0·17	0·25	0·19
TiO_2	0·49	0·52	0·42	0·42
P_2O_5	0·07	0·19	0·06	abs.
MnO	tr.	tr.	0·01	0·01
C	0·04	1·17	p.n.d.	—
	100·15	100·65	100·03	99·56
Sp. Gr. ..	2·68	2·68	2·71	2·67

I. Grey graptolite-bearing slate. Near mouth of Ingram's Creek. Anal. G. A. Joplin.
II. Chiastolite-slate with graptolite remains. Gygederick Hill, near Berridale. Anal. G. A. Joplin.
III. Dark grey slate (slightly micaceous). Wambrook Creek at crossing of Adaminaby Road. Anal. G. A. Joplin.
IV. Quartz-chlorite-mica-schist. East of McCarthy's Crossing, Por. 144, Par. of Coolringdon. Anal. G. A. Joplin.

Under the microscope the siliceous pelites are extremely fine grained and usually show banding. The recognizable constituents are tiny grains of quartz, occasional zircons and in some varieties numerous minute flakes of sericite. These occur in an almost isotropic faintly-greenish base which is possibly massive chalcedony or very finely-divided quartz. Rutile needles often occur in this isotropic material and haematite is sometimes present. The darker rocks contain finely-divided carbonaceous material often arranged in bands (Fig. 1B). Types from Wambrook Creek, the Berridale Road near Slack's Creek and near the mouth of Bulga Creek show a slight schistosity owing to the development of sericite. The schistosity may cross the bedding, which is indicated by the presence of more sandy bands. Some types show a little incipient biotite, no doubt due to slight contact alteration by the Berridale granite. Sometimes small cavities indicate negative crystals of pyrites.

Secondary silicification is a common feature of these rocks, which often contain small quartz veins or minute patches of fibrous chalcedony. In selecting material for analysis care was taken to avoid types showing this feature, although it seems likely that the secondary silica occurring in microscopic veins and patches represents only an internal rearrangement in the original rock.

Three siliceous pelites have been analysed. Analysis I (Table 2) represents a graptolite-bearing greyish-white slate from which most of the carbon has been removed. The removal of carbon and the leaching of the more soluble constituents of the rock concentrate the less soluble, so this may account for the higher silica and magnesia in this analysis. Analysis IV represents a psammite from the Binjura Beds in the lower part of the chlorite-zone which, except for its slightly higher magnesia, compares closely in composition with the siliceous pelites.

(2) *The Contact-Aureole of the Berridale Granite.*

In the area investigated, this aureole is wholly within the Coolringdon Beds, and as this unit consists almost exclusively of siliceous types there is little variety among the contact-rocks. Moreover, in most cases the contact-effects are not well marked, due no doubt to the fact that the rocks were already stable under low-grade regional conditions. Furthermore, there is some evidence to show that the Berridale granite was injected under comparatively low temperature conditions. In the case of rocks that were schistose prior to this metamorphism, the earlier structure is preserved.

When argillaceous material was present in the low-grade schist the superimposed contact metamorphism has produced incipient biotite and occasionally cordierite. On the Middlingbank Road, near Coolringdon, and on Gygederick Hill, near Berridale, chiastolite is developed in the carbonaceous siliceous slates (Table 2, Anal. II, and Fig. 1C). This rock, except for its slight schistosity, is almost identical with one described as an andalusite-cordierite-hornfels (Class I) by Goldschmidt (1911, Pl. i, fig. 1). Nevertheless, only the quartzites, which represent the rather abundant psammitic type, have a true hornfels structure and show no trace of schistosity.

4. BINJURA BEDS.

A. ROCKS OF SEDIMENTARY ORIGIN.

(1) *Chlorite and Biotite Zones.*

(i) *Aluminous Pelites.*

In the chlorite-zone these rocks are represented by dark grey or greenish-grey phyllites often showing corrugation or false cleavage.

Under the microscope directional structures are well marked and schistosity and foliation may be developed (Fig. 2, IA). The chlorite usually occurs in large plates parallel to the schistosity, but in a specimen from Por. 132, Parish of Coolringdon, which is high up in the chlorite-zone, the chlorite appears to be developed in an aggregate of minute flakes. Its colour varies from almost colourless to deep greenish-brown and is very patchy in its distribution. The mineral is negative with a birefringence varying from nothing to 0·003, $\alpha' = 1{\cdot}575$, thus the variety is pennine (Winchell, 1927). The chlorite plates or aggregates contain folia or tiny scattered scales of sericite, small octahedral inclusions of magnetite and a dusting of fine carbonaceous material. Detrital zircons are sometimes fairly abundant as inclusions, and patches of incipient green mica may occur.

Although the banded psammopelitic types are dealt with in a separate section, few of the pelites are entirely free from psammitic seams, which contain a little green mica in addition to the chlorite.

On the eastern margin of the chlorite-zone, adjacent to the biotite-zone, the foliation is more marked, false cleavage is more pronounced and the grainsize is coarser. In this sub-zone chlorite is being replaced by green mica, and in sections perpendicular to

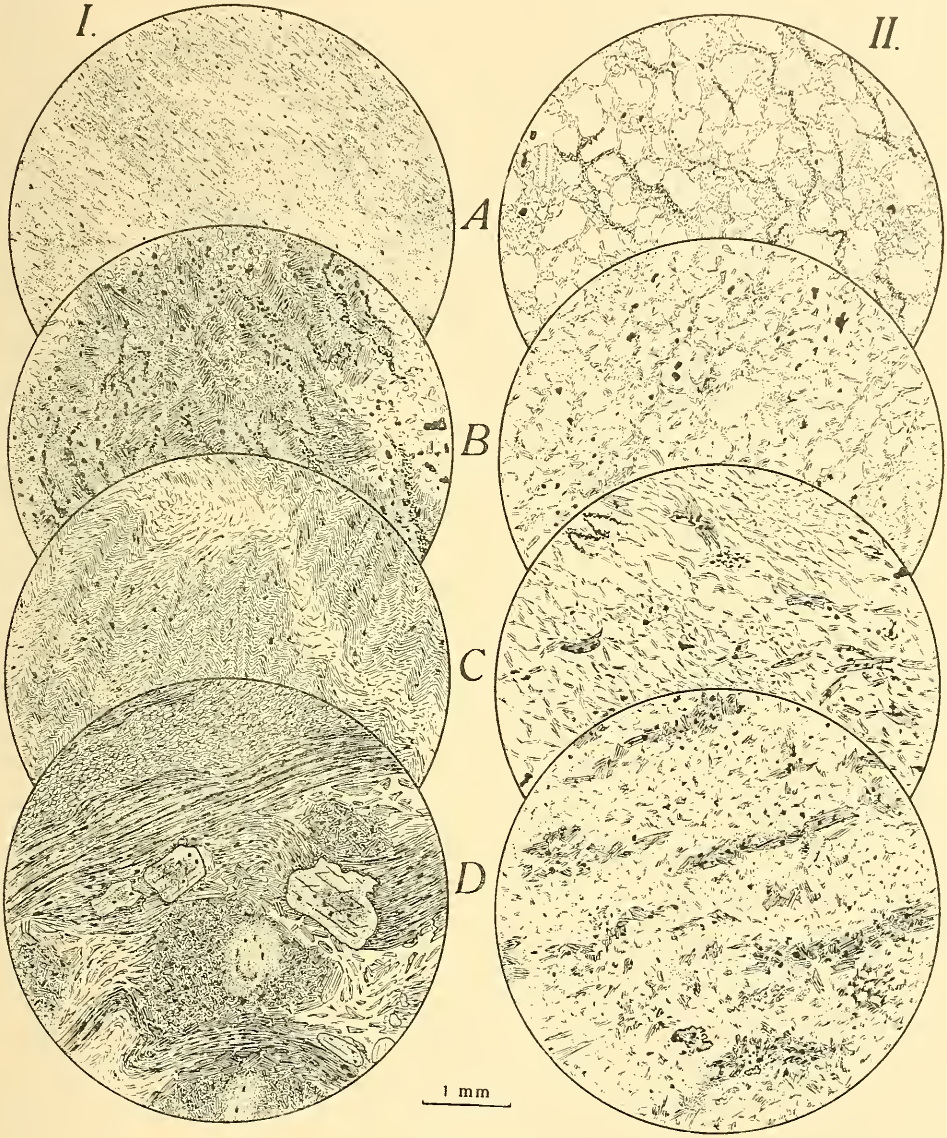

Fig. 2.
Vertical arrangement is iso-chemical and horizontal iso-gradal. (All × 12.)

I. *Aluminous Pelites.*

A. Chlorite-sericite-phyllite showing large plates of pale green chlorite, orientated flakes of sericite and a little quartz and iron ore. (*Chlorite-zone.*)

B. Chlorite-mica-schist showing development of green mica in deep green chlorite. A psammitic seam consists of green mica and quartz. (*Base of chlorite-zone.*)

C. Plicated mica-schist. The false cleavage is interrupted by a psammitic band. The rock consists mainly of quartz and mica and a little chlorite. (*Biotite-zone.*)

D. Andalusite-bearing mica-schist. The earlier schistosity is preserved in this contact type, which consists of andalusite and incipient crystals of chlorite associated with chlorite and reddish-brown biotite. The psammitic seam consists mainly of quartz and biotite. (*Andalusite-zone.*)

the schistosity wisps and bunches of white and green mica are developing along the axes of miniature folds (Fig. 2, IB). In sections parallel to the schistosity, chlorite and mica are intergrown in such a way that the chlorite appears to have a skeleton structure. In the associated psammitic bands xenoblasts of quartz, chlorite, green mica and a little brown mica are intergrown, and magnetite may be fairly abundant.

In the biotite-zone these rocks appear in the field as mica-schists with well-marked schistosity and often with a fine plication. Under the microscope they are seen to contain biotite, green mica, quartz and chlorite. Accessory minerals are magnetite, zircon, graphite and rutile.

Most types are slightly banded, and the development of biotite has advanced further in the more sandy seams. The pelitic seams usually consist of a dense mass of chlorite and green mica in which are embedded orientated flakes of biotite, especially well developed on the margin of the seam. A little quartz occurs in the pelitic bands, and this is the main constituent of the psammitic seams. In the plicated types chlorite (var. pennine) usually occurs in the troughs or crests of the miniature folds which are interrupted by the psammitic seams (Fig. 2, IC). Flakes of mica adjacent to quartz show a slight zoning with brown biotite core and greenish margin. In a few types quartz xenoblasts are somewhat elongated, and a large proportion obeys the Trener Rule with their optic axes perpendicular to the schistosity.

TABLE 3.

	A.	I.	II.	III.	IV.	B.
SiO_2	52·91	57·07	54·18	58·87	56·40	56·52
Al_2O_3	24·49	20·95	25·48	21·25	23·25	23·13
Fe_2O_3	5·45	4·27	2·99	2·47	1·30	1·96
FeO	1·50	2·42	3·08	4·05	5·22	5·09
MgO	1·80	3·08	3·13	2·98	3·24	2·82
CaO	0·29	0·14	0·41	0·12	0·63	0·39
Na_2O	1·08	0·42	0·73	0·60	0·61	0·24
K_2O	6·60	4·50	5·70	5·73	5·65	6·14
H_2O+	3·81	3·71	2·88	2·59	2·77	2·27
H_2O-	0·61	1·03	0·48	0·22	0·30	0·20
TiO_2	0·83	0·82	0·73	0·84	0·57	1·17
P_2O_5	0·10	0·06	0·07	0·05	0·06	0·22
MnO	0·06	0·05	0·03	0·02	0·01	0·06
C	0·19	1·33	0·34	0·16	0·51	—
CO_2	—	0·74	—	—	—	—
BaO..	0·06	n.d.	n.d.	n.d.	n.d.	0·11
	99·78	100·59	100·23	99·95	100·52	100·32
Sp. Gr.	—	2·76	2·80	2·78	2·85	—

I. Chlorite-sericite-phyllite. West of Slack's Ck., Por. 154, Par. of Coolringdon. Anal. G. A. Joplin.
II. Chlorite-sericite-phyllite. About ½ mile east of McCarthy's Crossing, Por. 144, Par. of Coolringdon. Anal. G. A. Joplin.
III. Plicated mica-schist. Slack's Ck. at crossing of Dry Plain Rd. Anal. G. A. Joplin.
IV. Knotted andalusite-schist. Slack's Creek, Por. 137, Par. of Binjura. Anal. G. A. Joplin.
A. Slate. Eastern slope of Mt. Wagra, near Tallangatta, Victoria. C. M. Tattam. *Geol. Surv. Vict.*, Bull. 52, 1929, p. 35.
B. Andalusite hornfels. Nooroongong. Ibid.

Explanation of Fig. 2 (*continued*).

II. *Psammites.*

A. Quartz-chlorite-sericite-schist showing clastic grains of quartz and felspar in a slightly recrystallized matrix of chlorite, sericite and haematite. (*Chlorite-zone.*)

B. Quartz-chlorite-mica-schist. Clastic structure only just discernible. The rock consists mainly of quartz, felspar, green mica and chlorite. Compare psammitic seams in IB. (*Base of chlorite-zone.*)

C. Quartz-biotite-schist. Schistosity marked by elongated grains of quartz and felspar and parallel flakes of biotite. Compare seam in IC. (*Biotite-zone.*)

D. Contact-altered quartz-biotite-schist preserving earlier schistosity. A little andalusite is shown near the bottom of the figure. (*Andalusite-zone.*)

Analyses of four aluminous pelites, one of them a contact type from the andalusite-zone, to be described later (see p. 169), are compared with two similar Ordovician rocks (Tattam, 1929) from Victoria in Table 3. Analysis I represents a rock high in the chlorite-zone and II is a little lower in the same zone. Analysis III (Fig. 2, IC) is of a biotite-schist containing a slightly greater percentage of quartz. Although there is some variation in these analyses, it is of an order which can be expected in sediments, and they obviously belong to an iso-chemical rock-series. A slightly different type, found in the andalusite-zone, appears to be very closely related (see Analysis, p. 169).

(ii) *Psammites.*

(*a*) *With an Argillaceous Matrix.*—Handspecimens of these rocks from the chlorite-zone show little evidence of alteration. They occur as light coloured buff, grey or white sandstones or quartzites usually interbedded with the phyllites.

Under the microscope a clastic structure is still apparent, but quartz and felspar grains are often slightly elongated and the matrix has recrystallized into a fine mosaic of quartz and felspar with minute flakes of chlorite and sericite. A little green mica is often present, but, as in the case of the pelites, this is more abundant as the biotite isograd is approached. Sometimes trails of parallel fibres of chlorite and mica are developed in the matrix at the extremity of the clastic grain and this has produced a slight schistosity. Andesine ($Ab_{63}An_{37}$), orthoclase and microcline have been recognized as detrital grains in addition to the very abundant quartz, and rutile and tourmaline are not infrequently present. Detrital grains of quartz may show undulose extinction, webs of minute rutile needles or trails of fluid pores at right angles to the incipient schistosity. The ferruginous types contain flakes of haematite in the matrix and the mica and chlorite are stained by iron oxides. In the more micaceous types a false cleavage may be developed.

As the biotite-zone is approached these rocks occur as sandy schists with a definite sheen and sometimes with a slight corrugation.

Under the microscope foliation and schistosity are marked by somewhat elliptical patches of granular quartz and by the parallel orientation of chlorite, white mica and green mica, which is developed a little earlier in these rocks than in the intercalated pelites (Fig. 2, IIB).

In the biotite-zone the original clastic structure is rarely preserved, though there are occasional examples of large elongated units of quartz surrounded by a fine mosaic of quartz and biotite. These areas appear to be recrystallized detrital grains rather than folia. A rock from Pors. 6/53, Parish of Jillamatong, is low in the biotite-zone and shows a definite clastic structure (see Harker, 1932, p. 230).

These rocks are now quartz-mica-schists, and a well-marked schistosity is shown by the elongated areas of quartz and felspar and by the parallelism of mica flakes (Fig. 2, IIC). In most cases elliptical areas of quartz consisting either of a single grain or of a group of small xenoblasts are outlined by flakes of mica, giving the rock a slightly lepidoblastic structure. Andesine is a constant constituent of these schists and a little green mica and pennine are usually present. Accessory minerals are magnetite, tourmaline, sphene and zircon. In one type muscovite is abundant.

Only one rock of this type has been analysed and its composition is closely comparable to that of the siliceous pelites (Table 2, Anal. IV). It occurs just within the biotite-zone, but shows some of the characteristics of rocks found near the base of the chlorite-zone.

(*b*) *With a Tuffaceous Matrix.*—On the Berridale Road about ¼ mile east of Slack's Creek greenish-grey tuffaceous sandstones are interbedded with a siliceous pelite. The outcrop occurs in the road-cutting, but cannot be traced for very far owing to overlying basalt. The pelite appears to be in the zone of clastic mica, but the partial recrystallization of the psammite suggests that it is near the chlorite isograd. The pelite is similar to those of the Coolringdon Beds whilst rather similar psammites are found in the higher grades of metamorphism to the east. It is assumed, therefore, that these rocks are at the top of the Binjura Beds and just within the zone of clastic mica.

Under the microscope a blastopsammitic structure is apparent (Fig. 3A). The rock consists of rounded and sub-angular fragments of quartz, felspar, hornblende and a fine-grained rock which might be felsite or quartzite. The matrix is a fine mosaic of quartz, felspar, amphibole, sphene and iron ore. Clastic grains of somewhat fibrous hornblende are terminated by tiny rods of recrystallized amphibole, which appear to be actinolite. A similar enlargement of clastic amphiboles by fine actinolite outgrowths has been recorded in low-grade green-schists by Tilley (1938) and by Hutton (1940). The clastic hornblende is negative with positive elongation, $Z \wedge c = 18°$, X = pale yellowish-green, Y = pale olive-green, Z = bluish-green. The recrystallized actinolitic type also occurs in aggregates of small rods in the matrix. Andesine ($Ab_{62}An_{38}$) occurs as small clastic grains and is also present in the recrystallized matrix. A little sericite occurs in the matrix and the parallel orientation of these flakes together with a slight elongation of quartz grains and the parallelism of amphibole rods has produced a slight schistosity, which, however, is not discernible in the handspecimen.

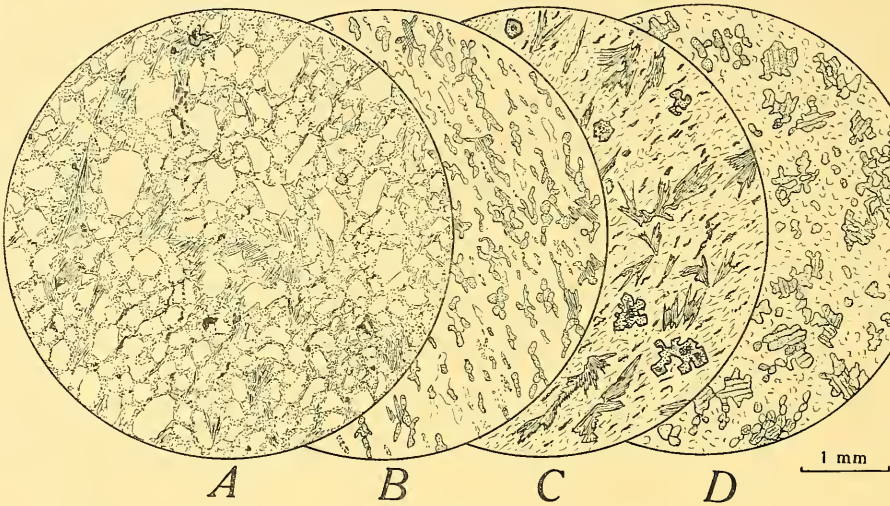

Fig. 3.

A. Tuffaceous psammite with clastic structure. Detrital grains of quartz, hornblende and felspar in a matrix of hornblende, felspar, quartz and iron ore. Berridale Road near Slack's Creek. × 12.

B. Clinozoisite-quartz-granulite. A little plagioclase and sphene are also present. Por. 109, Par. of Coolringdon. × 12.

C. Amphibole-garnet-granulite. The groundmass consists of a mosaic of quartz and plagioclase. Slack's Creek, Por. 154, Par. of Coolringdon. × 12.

D. Pyroxene-granulite. The light coloured minerals are plagioclase and quartz. Slack's Creek, Por. 137, Par. of Binjura. × 12.

Associated with this tuffaceous psammite is a finer-grained type containing a greater proportion of tuffaceous matrix and less clastic quartz and felspar.

Low in the chlorite-zone near the biotite isograd, and probably within the green mica sub-zone, a single specimen of light grey granulite has been collected. This occurs west of Slack's Creek in Por. 109, Par. of Coolringdon. Under the microscope, schistosity is well marked by the elongation of quartz and felspar grains and by bead-like strings of clinozoisite granules (Fig. 3B). Remnants of clastic amphibole are surrounded by epidote and clinozoisite, and their cores often appear clouded by the development of minute granules of sphene and iron ore. A little new amphibole may be intergrown with epidote and clinozoisite, and there is a little labradorite ($Ab_{48}An_{52}$) intergrown with the quartz and sometimes surrounding the clinozoisite. This possibly foreshadows the development of plagioclase within the biotite-zone.

In the biotite-zone these rocks occur as lenses of grey granulite. They show a well-marked schistosity and consist of quartz, labradorite, amphibole, sphene, iron ore, a little apatite and sometimes pale pink garnet.

The amphibole occurs in sheaves, in elongated feathers or in radiating bunches usually arranged in parallel bands (Fig. 3C). These are interleaved with a fine mosaic of quartz and felspar ($Ab_{40}An_{60}$), and the labradorite sometimes occurs in small poikiloblasts enclosing granules of quartz. Sphene may be fairly abundant and when it occurs as inclusions in the amphibole, it is surrounded by a small greenish-brown halo.

In the garnetiferous types this mineral occurs as small subidioblastic crystals or in groups of granules showing ill-defined crystal outlines. The core of the crystal is dark and cloudy and the clear outer rim is colourless in thin section. It seems likely that these garnets are manganiferous (Tilley, 1926*b*), as suggested by Analysis II, though it is possible that they may be rich in lime—either chemical characteristic might account for their premature development here. The constitution of this garnet and of the amphiboles in this group of rocks is worthy of further investigation.

There is a good deal of variation in the relative proportions of clastic grains to matrix in these rocks, thus it is to be expected that there will be marked variations in the chemical composition. Furthermore, if the matrix be tuffaceous, this may vary in constitution as well as in amount. Only two of these rocks have been analysed, and a casual comparison would seem to indicate no relationship between them. They are definitely siliceous types, and it will be seen that they compare with the psammite (Table 2, Anal. IV) and the more siliceous psammopelites (Table 5, Anals. III and IV) with regard to their silica and alumina. The total iron and magnesia compares with the siliceous psammopelites, but there is a marked difference in the lime and potash. Potash is distinctly lower in these rocks, and though the two analyses vary in the amount of lime, this oxide is much higher in both than in any other sedimentary rock analysed from this district. The clinozoisite type from the base of the chlorite-zone, like certain contact-altered pyroxene-bearing types to be described later, possibly contains a still greater amount of lime, and the development of garnet may be correlated with this chemical peculiarity.

TABLE 4.

	I.	II.
SiO_2	76·90	71·26
Al_2O_3	8·87	12·42
Fe_2O_3	1·85	0·68
FeO	2·98	4·47
MgO	2·72	2·13
CaO	2·75	7·73
Na_2O	2·41	0·31
K_2O	0·19	0·01
H_2O+	0·94	0·19
H_2O-	0·40	0·02
TiO_2	0·30	0·47
P_2O_5	0·06	abs.
MnO	0·02	0·55
CO_2	abs.	0·13
C	tr.	abs.
	100·39	100·37
Sp. Gr.	2·68	2·79

I. Tuffaceous psammite. Berridale Road, about ¼ mile east of Slack's Creek. Anal. G. A. Joplin.
II. Amphibole-bearing granulite. Slack's Creek, Por. 137, Par. of Coolringdon. Anal. G. A. Joplin.

(iii) *Psammopelites.*

As indicated above, the term psammopelite is used here only in a textural sense to mean rocks that consist of a mixture of coarse and fine material. The psammite and pelite may form an intimate mixture and give rise to homogeneous psammopelites or they may be arranged in alternating layers to form banded rocks.

These rocks need only brief description, for although by far the commonest types at Cooma, they are very similar to types that have already been described. Thus the unbanded homogeneous rocks, except for their greater proportion of fine pelitic matrix, are similar to the psammites with an argillaceous matrix (see p. 165) and the banded rocks, except for their characteristic alternating psammitic and pelitic layers, show no feature that distinguishes them from the two types already described. It will be remembered (see p. 162) that the pelites are rarely completely free from some psammitic seams and with an increase of these the rocks pass into the banded psammopelites.

Although banded types occur throughout the Binjura Beds, they are more noticeable in the higher grades of metamorphism, where the banding is often cross-cut by the schistosity. It will be shown that the pelites soon lose their identity on entering the granitized zone, but the banded psammopelites preserve theirs for a considerable distance and form the prominent type referred to below as the Corduroy Granulite. Two rocks of this type have been analysed and as they appear to have suffered little or no granitization, they are included in this section of the paper with analyses of other banded rocks. Although the contact-altered rocks are dealt with below, it might be mentioned here that a rock consisting of aluminous pelite and tuffaceous psammite (Table 5, Anal. I) occurs in the contact-zone and its analysis compares with a rock from Victoria (Tattam, 1929).

TABLE 5.

	I.	A.	II.	III.	B.	IV.
SiO_2	66·26	66·80	66·08	68·06	72·50	73·64
Al_2O_3	17·38	15·80	16·29	16·32	13·72	13·89
Fe_2O_3	0·24	1·62	2·22	0·99	0·56	0·70
FeO	3·01	3·63	3·62	4·15	3·49	4·04
MgO	2·63	2·25	2·87	2·21	2·24	1·98
CaO	1·02	0·47	1·17	1·09	0·63	0·28
Na_2O	2·63	1·00	1·32	1·29	0·98	1·12
K_2O	4·26	5·02	3·51	3·59	3·49	2·88
H_2O+	1·65	2·10	} 2·22	0·93	1·26	0·42
H_2O-	0·15	0·34		0·11	0·20	0·07
TiO_2	0·42	0·69	0·62	0·63	1·19	0·63
P_2O_5	0·23	0·66	0·05	0·19	0·08	n.d.
MnO	0·04	0·08	0·02	0·04	0·04	0·06
BaO..	n.d.	0·10	—	n.d.	0·04	n.d.
S	—	0·04	—	—	—	—
	99·92	100·60	99·99	99·60	100·42	99·71
Sp. Gr.	2·75	—	—	2·76	—	2·78

I. Banded schist with alternating andalusite-bearing and amphibole-bearing seams. Contact-aureole of Cooma gneiss, 20 chains west of north-east corner of Por. 137, Par. of Binjura. Anal. G. A. Joplin.
II. Theoretical rock consisting of 40% of tuffaceous psammite (Table 4, Anal. I) and 60% of pelite (Table 3, Anal. III).
III. Corduroy granulite. Spring Creek, Por. 212, Par. of Binjura. Anal. G. A. Joplin.
IV. Corduroy granulite. Spring Creek, Por. 212, Par. of Binjura. Anal. G. A. Joplin.
A. Felspathic pinite gneiss. Ensay. C. M. Tattam. *Geol. Surv. Vict.*, Bull. 52, 1929, 38.
B. Cordierite hornfels. Indigo Creek. Ibid., p. 36.

Obviously there is much variation in the chemical composition of these rocks, and a long series of analyses would serve no useful purpose, but the three that have been made indicate types intermediate between pelite and psammite, and the calculated analysis adds further emphasis to this fact. It will be noted that the analysed rocks are contact-altered types, but it is believed that they are similar to the banded psammopelites in the chlorite and biotite zones, where banding is less distinct.

(2) *The Andalusite-Zone.*

The andalusite-zone surrounds the granitized zones at a distance of about 3¼ miles from the apparent margin of the gneiss. Its trend to the north suggests that the Ordovician intrusion had a northerly extension, now engulfed by the Silurian gneiss. This zone is part of the thermal aureole of the granite-gneiss, beyond the outer limit of granitization.

In the foregoing section on the chlorite and biotite zones, metamorphic changes have been traced in aluminous pelites, in psammites with an argillaceous and with a tuffaceous matrix, and in psammopelites including both homogeneous and banded types. In this section the contact alteration of each of these types will be considered.

The contact-aureole appears to have been superimposed upon the schists of the biotite-zone, and the earlier schistosity is usually well preserved. No true hornfelses occur, but the psammitic types form siliceous granulites sometimes with a hornfelsic aspect.

The outer margin of the andalusite-zone is well marked in the aluminous pelites by the development of knotted andalusite-schists, but the inner margin gradually merges into the permeation-zone and mapping is very difficult. Here the knotted silvery schists gradually give place to a more granular spotted rock, though the interbedded sandy and banded types may still be recognized. In mapping the inner margin of the andalusite-zone the appearance of the granular rock was taken to mark the outer edge of the permeation-zone, and though these rocks pass imperceptibly into the paragneisses (see p. 174), microscopic examination reveals that many of them are contact-altered schists with none of the characters of the paragneiss.

Like the aluminous pelites in the lower grades of metamorphism, these rocks are never completely free from sandy bands (Fig. 2, ID). Red-brown mica is developed in both pelitic and psammitic layers and in the former it occurs as elongated flakes with muscovite and gives the rock a well-marked lepidoblastic structure. In the psammitic seams it forms small xenoblasts intergrown with quartz. The micaceous seams, often much discoloured by carbonaceous material, are sometimes bent round large crystals of andalusite. Large flakes or aggregates of chlorite are also associated with these seams, and incipient crystals of cordierite may develop in the chlorite-mica aggregates (Fig. 2, ID). Both andalusite and cordierite contain carbonaceous inclusions. The analysis of a rock of this type is compared with other aluminous pelites in Table 3 and its similarity to a contact-altered schist from Victoria is noteworthy.

Further east, just within the margin of the permeation-zone, the contact-altered aluminous pelites show well-developed subidioblastic crystals of andalusite, usually crowded with quartz inclusions, in a lepidoblastic groundmass of brown and white mica and some xenoblastic quartz (Figs. 7A and 7B). Some of these rocks contain a greater abundance of white mica, and though structurally similar to the normal aluminous pelites in this zone, they differ chemically in containing less potash and more alumina. Lime is also higher in the only analysed rock of this type, and it is possible that, like the associated psammites, the sediment contained a little kaolinized felspathic tuff. An analysis of this type is:

SiO_2	54·92
Al_2O_3	26·84
Fe_2O_3	2·66
FeO	4·11
MgO	3·47
CaO	1·98
Na_2O	0·76
K_2O	2·19
H_2O+	2·25
H_2O-	0·16
TiO_2	0·68
P_2O_5	0·14
MnO	0·05
	100·21
Sp. Gr.	2·82

Anal.: G. A. Joplin.

Most types containing a great abundance of mica are poor in, or free from, andalusite and cordierite. A schist from the railway loop immediately north-east of Cooma contains an unusual amount of muscovite, and it is possible that free alumina has been combined with potash from either the Ordovician or the Silurian magma.

In a silvery schist from Por. 76, Parish of Binjura, sillimanite is developed in the white mica and andalusite is absent. In this rock, as well as in many others, idiomorphic crystals of tourmaline are probably introduced by the granite-gneiss magma.

The psammitic and psammopelitic rocks within the andalusite-zone show some structural evidence of contact-metamorphism. Sometimes hornfels structure is produced in the more sandy types and minute sedimentary bands are generally well preserved. The mineralogical changes in the pelitic material of these rocks is identical with those in the pelites themselves (Fig. 2, IID).

In a banded rock consisting originally of pelite and tuffaceous sandstone, the resulting contact-rock shows sharply-defined seams of andalusite-bearing pelite and amphibole-plagioclase-granulite.

With regard to the tuffaceous sandstones themselves, amphibole-plagioclase and amphibole-plagioclase-garnet assemblages are stable both in the biotite-zone and in the andalusite-zone, but within the latter a pyroxene-granulite also occurs (Fig. 3D) and, as mentioned above (p. 167), this may be due to a higher lime content in the original tuffaceous matrix.

(3) *Progressive Metamorphism in the Binjura Beds.*

The aluminous pelites behave quite normally in the chlorite and biotite zones (Barrow, 1912; Tilley, 1925; Harker, 1932), but further east the biotite-schists are contact-altered by the Cooma gneiss and finally pass, without apparent break, into granitized zones in which, as shown below (p. 177), the sillimanite-zone is incorporated. There is, therefore, a hiatus or metamorphic unconformity between the biotite-zone and the zones adjacent to the gneiss, the garnet and cyanite zones being absent. The possible reason for this break is considered below (p. 193).

In Table 3 four aluminous pelites are compared with two Ordovician rocks from North-Eastern Victoria (Tattam, 1929). The six analyses are arranged in such a way as to show progressive chemical changes in this rock-series. The high water and ferric iron content of the Mt. Wagra slate indicates that it is in a lower grade of metamorphism than any aluminous pelite at Cooma, and it is possibly within the zone of clastic mica. The andalusite hornfels from Noorongong compares closely with the contact-altered andalusite-bearing biotite-schist at Cooma, so these analyses have been placed side by side, but in such an order as to keep the four Cooma rocks in a group together. A glance at this iso-chemical series shows that ferrous iron increases at the expense of ferric as metamorphism progresses. Water shows a general decrease in the same direction, but other variations are due to original differences in the sediments.

Reference to the petrography will show that the psammites and the psammitic bands in the pelites at each stage give evidence of a slight advance of metamorphism over the adjacent pelites; thus in the psammite, green mica occurs fairly high in the chlorite-zone and biotite comes in towards its base. This is a direct contradiction to the observations of Harker (1932, p. 244), who considers that owing to the separation of matrix material by clastic grains and the limited diffusion in metamorphism, there is a lag in the psammite as compared with the pelite. The quantity of pore-fluid (MacGregor and Wilson, 1939) possibly has an important effect in promoting diffusion, and if this be abundant, as might be expected in rocks of recent consolidation (Joplin, 1935), metamorphism might be accelerated by the greater porosity of the psammite. On the other hand, Harker (1932, p. 230) has pointed out that a deficient shearing stress may be responsible for an early development of biotite, and gives examples of blastopsammitic rocks containing this mineral. Again, this response to thermal metamorphism may be more readily felt in the porous rock, owing to the presence of pore-fluids.

Chemical and mineralogical studies of the chlorites and micas in the pelites and of amphiboles and garnet in the tuffaceous psammites would be an interesting subject for investigation and would probably yield important results. It is regretted that it cannot be attempted here.

B. ROCKS OF IGNEOUS ORIGIN.

(1) *Mode of Occurrence.*

Hornblende-pyroxene-granulites occur abundantly within the area occupied by the Cooma gneiss (see Plate v), but their field occurrence is somewhat obscure. They are found occasionally as xenoliths in certain areas of the gneiss, but more often they are scattered about on its surface as loose pebbles. The occurrence of these pebbles suggests that they are derived from the gneiss. Although sedimentary xenoliths are far more abundant than the hornblende-pyroxene-granulites, it seems not unreasonable to assume that these micaceous types, like their gneissic host, are more susceptible to weathering, and that the very compact, more resistant basic granulites, thus weathering out and strewing the granite surface, give a false impression of the relative abundance of these xenoliths as compared with those of sedimentary origin.

Although they occur within the gneiss, the basic granulites are remarkably free from granitization—a fact noted by Read (1927*a*), who says: "Craig Dhu illustrates a marked feature of the Cromar Complex, namely, the resistance to injection and complexing shown by the rocks of the Greenstone Series as compared with the sedimentary country-rocks."

(2) *Petrography.*

In the handspecimen these rocks are dense dark green or black granulites which usually show a well-marked banding and a somewhat imperfect schistosity. The pyroxene-rich types are lighter green and the orientation is not so well marked as in the case of those richer in hornblende. They are often intersected by small quartz-felspar veins that appear to bear no relation to the schistosity. On the borders of these veins slightly larger crystals of hornblende have developed.

Under the microscope several types may be recognized. First there is a banded type free, or almost free, from pyroxene. The bands consist of alternating seams of hornblende and plagioclase or more often of a mosaic of these two minerals in different proportions (Fig. 4A). Another type is massive and shows an intergrowth of hornblende and pyroxene associated with plagioclase (Fig. 4B), and finally a banded type occurs in which plagioclase-hornblende seams alternate with plagioclase-pyroxene seams (Fig. 4C).

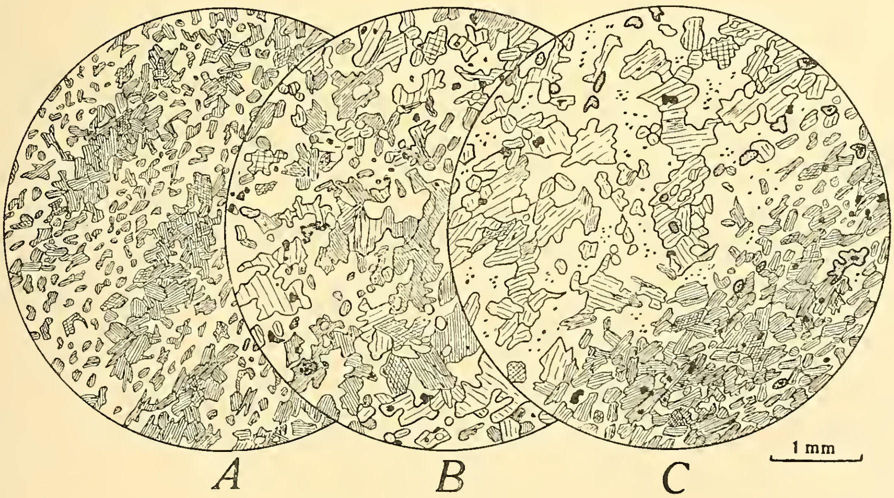

Fig. 4.

A. Banded hornblende-plagioclase-granulite. Cooma Creek near gorge. × 12.

B. Massive hornblende-pyroxene-granulite. Plagioclase, magnetite and sphene are also present. Cooma Creek. × 12.

C. Banded hornblende-pyroxene-granulite. Alternating seams of pyroxene-plagioclase and hornblende-plagioclase assemblages. Por. 12, Par. of Cooma. × 12.

In seams consisting mainly of hornblende, the amphibole is columnar with the longer axes parallel to the schistosity, and in those layers where plagioclase is abundant it occurs as xenoblasts intergrown with felspar.

Sphene inclusions are common and these may be surrounded with brown haloes.

Labradorite varies in composition from $Ab_{36}An_{64}$ to $Ab_{45}An_{55}$ and often contains small blebs of quartz (cf. Read, 1927*a*). In some granulites it occurs in poikiloblasts up to 1 mm., but is more often developed in small xenoblasts intergrown with the ferromagnesian minerals. Twinning is not common, but both albite and pericline types may occur.

In the veins that intersect these rocks the felspar is andesine $Ab_{53}An_{47}$. It occurs in allotriomorphic grains associated with quartz, apatite and sphene. At the border of the vein, large crystals of hornblende occur, and the felspar contains drop-like quartz inclusions indicating perhaps that they are xenocrysts derived from the granulite. Like the quartz-andesine veins injecting the amphibolites (Joplin, 1939), these veins possibly represent a phase of the granite-gneiss.

In the pyroxene-rich granulites the pyroxene is a diopsidic type occurring in subidioblastic columnar crystals and often intergrown with epidote. In some types the epidote is very abundant and may be visible in the handspecimen. In types containing hornblende, pyroxene may be intergrown with the amphibole or it may form distinct seams associated with plagioclase. The pyroxene often shows alteration into carbonates along cracks.

A pinkish type of sphene is well developed and usually idioblastic. Sphene may sometimes fringe a nucleus of iron ore (Fig. 4C). Iron ore, probably ilmenite, is not abundant, but is usually present in small granules.

TABLE 6.

	I.	II.	A.	B.	C.	D.	E.	F.
SiO_2	42·66	49·50	48·34	48·51	47·49	47·24	47·28	47·26
Al_2O_3	20·48	16·47	20·10	19·44	21·46	18·55	21·11	22·80
Fe_2O_3	1·15	0·72	1·97	5·66	1·72	6·02	3·52	2·21
FeO	10·16	9·10	6·62	4·00	4·80	4·06	3·91	5·41
MgO	5·64	7·47	5·49	5·12	4·59	5·24	8·06	7·76
CaO	16·70	14·79	13·16	12·03	13·24	11·72	13·42	10·93
Na_2O	0·57	0·47	1·66	2·53	2·17	2·42	1·52	1·72
K_2O	0·21	0·32	0·98	0·25	0·42	0·15	0·29	0·29
H_2O+	0·41	0·57	0·44	0·48	2·54	2·24	0·53	0·90
H_2O-	0·16	0·03	0·02	0·04	0·17	0·21	0·13	0·11
TiO_2	1·66	0·75	0·95	1·46	0·93	1·46	0·28	0·38
P_2O_5	n.d.	0·05	0·04	0·16	0·43	0·26	tr.	0·06
MnO	0·15	0·16	0·32	0·23	0·15	0·31	0·15	0·31
Etc.	—	—	0·21	0·11	0·12	0·24	—	0·10
	99·95	100·35	100·30	100·04	100·23	100·12	100·20	100·24

I. Hornblende-pyroxene-granulite. South of Amphibolite Quarry, Por. 12, Par. of Cooma. Anal. G. A. Joplin.

II. Hornblende-granulite (with trace of pyroxene). Cooma Creek, near entrance to gorge, Por. 135, Par. of Cooma.

A. Olivine-gabbro. Major Intrusion, Beinn na Duatharach, Mull. Anal. E. G. Radley. *Mem. Geol. Surv. Scot.*, 1924, 24.

B. Basalt (porphyritic central type) Tertiary lava. ⅝ mile north-east of cairn on Cruach Doire nan Guilean, Mull. Anal. E. G. Radley. Ibid.

C. Basalt (porphyritic central type) Tertiary lava. ¼ mile slightly east of south of cairn on Cruach Choireadail, Mull. Anal. E. G. Radley. Ibid.

D. Basalt (porphyritic central type) Tertiary lava. ½ mile south-south-west of Derrynaculen, Mull. Anal. E. G. Radley. Ibid.

E. Olivine-gabbro. Major Intrusion, Coir'a'Mhadaidh, Cullins, Skye. Anal. W. Pollard. *Mem. Geol. Surv. U.K.*, 1904, 538.

F. Biotite-eucrite. Ring-dyke Centre 3, Ardnamurchan. Bank of stream 1 mile east 33° south of Achnaha. Anal. E. G. Radley. *Mem. Geol. Surv. Scot.*, 1930, 85.

(3) *Nature of the Original Igneous Rock.*

The restricted occurrence of the basic granulites, as well as their close association with sedimentary types, suggests that they represent small sills or contemporaneous lava flows in the Binjura Beds.

Two of the basic granulites have been analysed and it will be seen from Table 6 that, with their low silica and magnesia and high alumina and lime, they bear a marked resemblance to igneous rocks of the Porphyritic Central Magma type (Bailey and Thomas, 1924).

To examine this relation further, the Cooma rocks, together with thirteen igneous rocks of the Porphyritic Central Magma type, have been plotted on an A-F-C diagram (Fig. 5). In using this type of diagram Eskola (1920) was guided by the mode of the rock in calculating amounts of magnetite, ilmenite and sphene, etc., but as the original

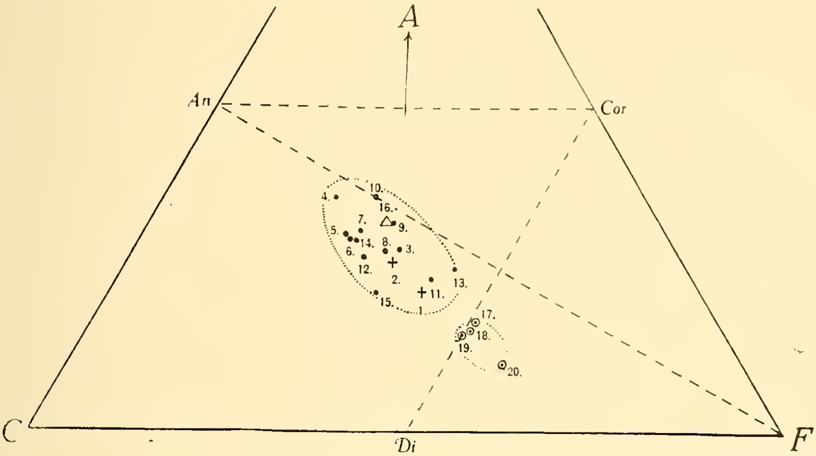

Fig. 5.—A-F-C Diagram showing plots of analyses of Porphyritic Central Magma type. 1 and 2 (+) = Cooma; 3 and 4 (●) = Skye; 5-9 (●) = Mull; 10-15 (●) = Ardnamurchan; 16 (△) = Tuffaceous psammite, Cooma.

For comparison analyses of Cooma amphibolites 17-20 (⊙) are also plotted.

mineral composition of the Cooma granulites is unknown, and the modes of the igneous rocks used for comparison are not available, a slight modification of Eskola's diagram has been used. Thus A = molecular proportion of alumina after satisfying alkalies, C = molecular proportion of lime after satisfying P_2O_5 and F = molecular proportion of $MgO + FeO$ after satisfying Fe_2O_3 and TiO_2. It will be seen that the fifteen analyses are crowded together and the dotted line enclosing them has been drawn to suggest the field of the igneous rocks of Porphyritic Central Magma type.

A tuffaceous psammite (Table 4, Anal. II) has also been plotted in this way and it will be seen that it falls within the igneous field. The other analysed psammite has not been included as it contains a greater admixture of detrital material and lies outside the field.

Thus the granulites bear chemical resemblances to igneous rocks and their field occurrence seems to suggest that they have been intercalated with sediments, some of which are related tuffs. They therefore possibly represent small sills or flows.

IV. Granitized Country-Rocks.

1. permeation-zone (country-rock dominant).

(1) *Field Occurrence.*

In dealing with the andalusite-zone it was pointed out that the boundary between this and the succeeding permeation-zone was a somewhat arbitrary one, determined in the field by the appearance of slightly more granular and less schistose rocks. Furthermore, it has been shown that contact-rocks, retaining all their normal microscopic characters, may be found well within this so-called permeation-zone.

This zone is essentially one of granitization, but one in which the sediments are markedly dominant, and though many of the reactions have been brought about by magmatic fluids, few of these active agents have been precipitated and their rôle appears to have been that of transporter and catalyst. The rocks altered by such fluids might still be regarded as paragneisses,* and the zone in which they are developed is essentially the sillimanite-zone (Barrow, 1893, 1912). At irregular distances from the inner margin of this zone, the paragneisses show definite evidence of granitization and the rocks are of the nature of permeation-gneisses. In the field it is impossible to distinguish between contact schists and paragneisses on the one hand and between paragneisses and permeation-gneisses on the other. As all these changes have been brought about by magmatic fluids, it is considered expedient to group these rocks as members of the permeation-zone, which is the outermost zone of granitization.

The permeation-zone varies in width from 1 to 2½ miles and is about 1½ miles from the apparent boundary of the gneiss. This zone is characterized by granulites and gneisses with a very distinctive appearance in the field. Browne (1914) noted a gneiss which he considered to be a highly contaminated intrusive rock antedating the Cooma gneiss. He called this the mottled gneiss on account of its characteristic mottling on weathered surfaces. To the associated banded granulite he gave the highly descriptive name corduroy granulite, again because of its weathering, which, in this instance, shows a ribbed or corded surface.

The zones of granitization are wholly within the Binjura Beds consisting of alternating aluminous pelites, psammites and psammopelites. In the andalusite-zone the country-rocks still retain their distinctive schistose characters, and in passing from this to the permeation-zone only very slight changes are apparent. The same alternation of strata may be observed, and though the rocks are more granular, the types recognized in the lower grades of metamorphism may still be discerned. Further into the permeation-zone, however, the aluminous pelites lose their distinctive schistose appearance and gradually pass to spotted granulites and then to mottled gneisses, though the interbedded psammopelites still retain their usual characters. Thus the interbedded pelites and psammopelites of lower grades are now represented by mottled gneisses and corduroy granulites.

Along Pilot Creek these rock-types may be recognized, but the permeation-zone in this northern part of the area is not typical.

Spring Creek, in the Parish of Binjura, might be regarded as a type-section for this zone, although the permeation-gneiss derived from the aluminous pelite does not occur here. Exposed in this creek is an alternating series of mottled gneisses and corduroy granulites, with the gneisses occasionally showing transgressive relations to the granulites. Transgressive boundaries are also well shown on the road near Mittagong Bridge. The field evidence on the origin of the mottled gneiss thus appears to be contradictory, for on the one hand it appears to be a bedded sedimentary rock and on the other an intrusive igneous one. On account of the occasional transgressive relation, Dr. Browne (1914) was inclined to the view that the gneiss was an intrusive rock usually with a concordant habit, but occasionally with a transgressive one. In this paper an endeavour will be made to show that the rock is essentially one of sedimentary origin.

Dykes of graphic pegmatite and of tourmaline pegmatite frequently invade rocks of the permeation-zone and this zone is further characterized by ptygmatic veins of quartz and pegmatite (Fig. 6). Sederholm (1907, p. 101) considers that such veins are introduced from the granitizing magma into semi-plastic sediments, thus envisaging a partial re-fusion or re-solution of the sediments. Read (1927*b*) has reviewed the various theories put forward to explain this type of folding and vein injection, and has himself concluded that those of Sutherland are due to injection into massive rocks. Taking examples of the Finnish occurrences he quotes Sederholm as saying that the ptygmatic veins occur in rocks "apparently more massive than the rest of the schists". The more granular and less schistose character of the Cooma permeation-zone has already been mentioned, and although the mottled gneisses are in no way massive, they are certainly more massive than the schists outside this zone where ptygmatic veining is almost absent.

---

* *Paragneiss* is used here to denote a banded or mottled sedimentary rock of high grade metamorphism (sillimanite-zone), that has received no addition from the magma as opposed to *Permeation-gneiss*, which contains some igneous material.

Holmquist (1922) regards the ptygmatic vein as an endogenous secretion of the country-rock itself under conditions of ultra-metamorphism, and it will be shown later that there is some evidence for believing that under the fluxing action of fluids from the magma, some of the pelitic rocks at Cooma were dissolved and re-precipitated as quartz-andalusite veins. These veins and secretions, however, are of microscopic dimensions and there is better evidence for regarding the ptygmatic veins as products of the gneissic magma. At present the origin of the ptygmatic veins at Cooma must remain an open question. The corduroy granulites sometimes exhibit mullion structure as noted by Browne (1931*b*). Good examples of this may be seen in Pilot Ck., Por. 124/125, Par. of Murrumbucka, and on a small creek, Por. 170, Par. of Jillamatong.

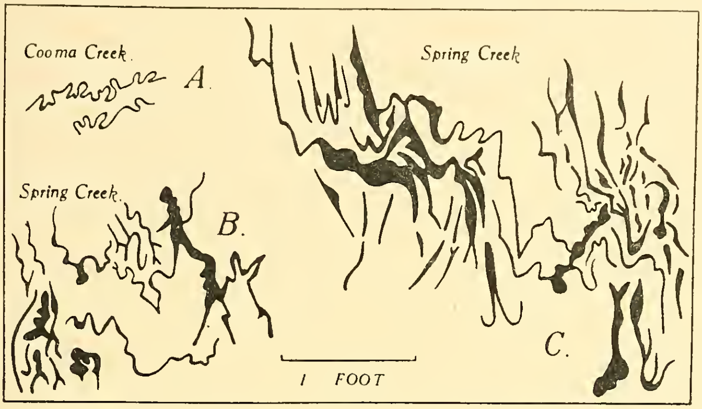

Fig. 6.—Ptygmatic quartz vein in mottled gneiss.

(2) *Petrography.*

(i) *Mottled Gneiss derived from Aluminous Pelite.*

As previously mentioned, contact-altered types, retaining all their usual microscopic characters, are found on the margin of, or often well within, the permeation-zone. In handspecimen these rocks are distinctly schistose and though very slightly granular, show very close resemblances to the characteristic knotted schists of the contact-aureole. Andalusite-bearing schists just within the permeation-zone, and a more micaceous type of somewhat different composition are described on p. 169. Although differing chemically the micaceous rock is structurally similar to the other contact-altered pelites, and both types may be regarded as the foundation of the pelite-derived mottled gneiss.

Slightly more altered rocks of this zone are represented by fine, granular, somewhat schistose types with ill-defined elliptical spots that give the weathered surface a mottled appearance. These are interbedded with the corduroy granulites and occur on the outer margin of, or just within, the permeation-zone.

Under the microscope the spots are seen to consist of rounded areas of the typical contact-altered andalusite-biotite-schist (compare Figs. 7B and 7C), which are partly surrounded by small (0·3 mm.) orthoclase porphyroblasts crowded with rounded blebs of quartz and outlined with small flakes of biotite. In appropriate sections the porphyroblasts are seen to be slightly elongated in the direction of the schistosity and the mica flakes are orientated.

The envelopment of fine-grained andalusite-biotite-schist by coarser material, possibly of the same chemical composition, is of interest as a somewhat similar phenomenon has been observed by Barrow and Craig (1912). They considered the finer fragments to be hornfelses that were formed as the result of an earlier intrusion and were subsequently crushed and subjected to high-grade regional metamorphism; but it will be seen below that a somewhat different explanation is put forward to account for the Cooma occurrence.

Iron ores are usually absent from these Cooma rocks, but a little magnetite sometimes occurs in groups of small grains. Zircons, with their characteristic haloes, often with a corona, are common as inclusions in the fine-grained schist fragments. In these

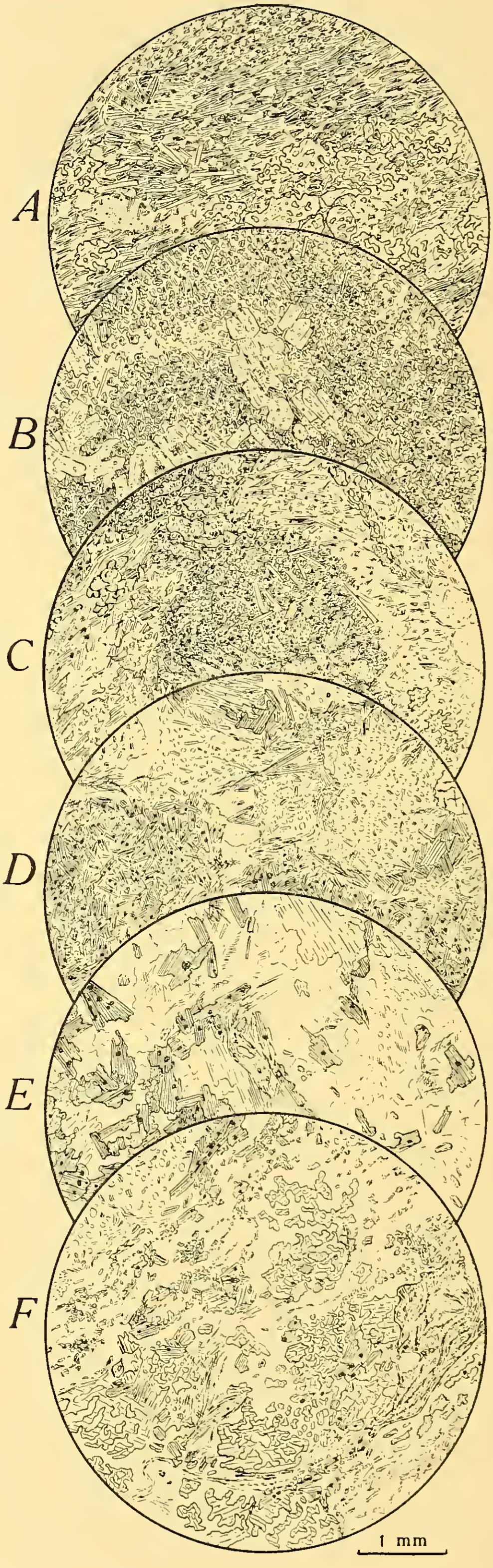

Fig. 7.

A. Contact-altered schist showing andalusite, biotite, muscovite, altered cordierite and small xenoblasts of quartz. Section parallel to schistosity. × 12.

B. Similar rock cut perpendicular to schistosity. × 12.

C. Spotted granulite showing 'budding' of schist and development of orthoclase porphyroblasts. × 12.

D. Sillimanite-gneiss (Paragneiss). Further stage in development of mottled gneiss. Schist remnants more isolated and coarser in grain. Sillimanite and new andalusite associated with porphyroblastic orthoclase. × 12.

E. Mottled gneiss. Schist remnant (left) coarser in grain and broken up by development of muscovite, quartz and striated orthoclase. Note sillimanitization of biotite in centre of figure. × 12.

F. Andalusite-quartz segregation in paragneiss (cf. Fig. 7D). Note isolation of schist remnant now represented by sillimanitized biotite (right). × 12.

rocks zircons are more abundant than in the granite-gneiss itself; a fact noted in similar rocks by Lacroix (1899, p. 8). Occasionally large (1 mm.) crystals of andalusite, clear and free from inclusions, form adjacent to, or just within, the schist remnant, and granular quartz and large flakes of brownish-red biotite are usually associated. At a slightly later stage this andalusite-quartz-haughtonite assemblage forms tiny veins or segregations within the schist fragment, and still later such veins cross-cut the whole rock (Fig. 7F). These may perhaps be compared with the oligioclase-quartz segregations and veins in the garnet-sillimanite-gneiss of Glen Muick (Barrow and Craig, 1912).

When lobes of the fine-grained schist have been completely detached and isolated in the coarser matrix of porphyroblastic orthoclase, there is a development of sillimanite, which is at first evidenced by the appearance of tiny trails, mats or needles at the margin of the schist fragment and a little later between the orthoclase porphyroblasts (Fig. 7D). When this occurs there is usually a noticeable increase in the size of the criss-cross mica flakes and in the proportion of the white mica in the schist fragments. Moreover, these larger flakes of muscovite are usually poikiloblastic. The rocks might now be called paragneisses or sillimanite-gneisses and the region in which they occur is essentially the sillimanite-zone, the relict andalusite being in unstable equilibrium.

In handspecimen the rocks now show a less schistose appearance and might be termed mottled gneisses or granulites. Under the microscope the schist remnants are still recognizable and, with few exceptions, their texture is coarser (Fig. 7D) and their size much reduced. They now contain more quartz and muscovite and are frequently intersected or completely surrounded by large crystals of andalusite and reddish biotite. Small scattered grains of partly-pinitized cordierite are often associated with the disintegrating schist fragment. Orthoclase porphyroblasts have now attained a size of about 2 mm. and are outlined by large flakes of biotite and matted strands of sillimanite filaments. Sillimanite also occurs in slender needles or in radiating tufts in both quartz and orthoclase. The orthoclase porphyroblasts may be mantled by quartz or optically-continuous orthoclase, which is often separated from the original felspar by a barrier of sillimanite growing out into the clear rim. Small patches of myrmekite sometimes encroach on the margins of the porphyroblasts and occasional veinlets and small grains of striated orthoclase may occur. The rocks are now passing from paragneisses to permeation-gneisses, as it is believed that the striated orthoclase, the myrmekite and some of the quartz are additions from the magma.

In most cases the original schist fragments are now represented either by fairly coarse areas of criss-cross micas associated with relict andalusite and large crystals of new andalusite, biotite and quartz, or by large porphyroblasts of pink, pleochroic andalusite with rounded inclusions of red mica and quartz. The development of sillimanite both from andalusite and from biotite is now well shown and knotted patches of this mineral with a faint brown colour and showing ghosts of pleochroic haloes often mark the positions of original flakes of biotite (Tilley, 1921; Tattam, 1929). Occasionally such patches of knotted and gnarled sillimanite are completely surrounded by the quartz-andalusite segregation material (Fig. 7F). At this stage also large crystals of andalusite are often surrounded by small rods of sillimanite. The orthoclase porphyroblasts may be wedged apart by the development of striated orthoclase (Browne, 1922, p. 33) and themselves show perthitic intergrowth with albite.

These rocks pass imperceptibly into a group that cannot be distinguished from them in the field. The rocks are now true permeation-gneisses. Mottling is still pronounced and under the microscope the small schist fragments may still be recognized, but they are coarser in grain and partly disintegrated by the development of large plates of muscovite and poikiloblastic grains of cordierite. The earlier formed muscovite flakes are poikiloblastic, but the new larger crystals are moulded around the earlier minerals and are practically free from inclusions. At this stage muscovite, together with large grains of quartz, striated orthoclase or microperthite and abundant myrmekite, occurs in the coarse matrix. Needles and mats of sillimanite are common in the muscovite and quartz, and occasionally occur in the orthoclase (Fig. 7E). The felspar porphyroblasts have now almost completely disappeared, but traces of them may be represented by groups of small rounded inclusions at the centre of large irregular felspar grains.

Cordierite occurs at first as irregular grains in or near the schist fragment, but in the last stages of its disintegration the cordierite may be completely surrounded by quartz and orthoclase, and occurring thus, the mineral is idioblastic and tabular. Small crystals of apatite are now prominent and part of the rock has a distinct igneous appearance.

Besides the development of myrmekite other intergrowths and symplektites occur. Quartz-muscovite symplektites occur around orthoclase and cordierite grains giving the rock a somewhat porphyroblastic appearance. Sederholm (1916) has observed this intergrowth fringing orthoclase, but does not record its association with cordierite. In one specimen a vein of orthoclase invades a fragment of relict schist, and where adjacent to andalusite, it is bordered by a narrow scolloped rim of quartz crowded with sillimanite needles. Against the orthoclase the quartz forms a series of tiny fans, and the tufts of sillimanite radiate from their base which is adjacent to the andalusite.

(ii) *Mottled Gneiss derived from Psammopelite.*

(*a*) *Corduroy Granulite Foundation.*—In the early stages of their development these rocks are essentially contact-rocks. In handspecimen they are well banded and on account of the differential weathering of the bands a characteristic ribbed or corduroy structure is produced. In the normal types the bands are fairly evenly spaced, but in the rarer, more siliceous varieties there is a wider separation of the dark bands. The light bands are the less susceptible to weathering and form the ridges.

Under the microscope the light bands are seen to consist mainly of a granoblastic mosaic of quartz, biotite and orthoclase with possibly a little untwinned plagioclase. The dark bands contain abundant biotite, granular andalusite and a little quartz. A little muscovite may be present in either band, and tourmaline, zircon and iron ores are common accessories. The bands are about 1·5 mm. in width and the grainsize of the rock is 0·1 mm. or less (Fig. 8A).

The banding is undoubtedly of sedimentary origin, but the arrangement of mica flakes indicates an approximate parallelism of bedding and schistosity. A false cleavage is sometimes evident in the micaceous seams. The biotite may be reddish-brown or greenish-brown.

At a slightly later stage in the development of the gneiss, the light bands show small orthoclase porphyroblasts with a sieve structure, and gradually these encroach on the darker bands, which consequently become discontinuous and are marked by a series of

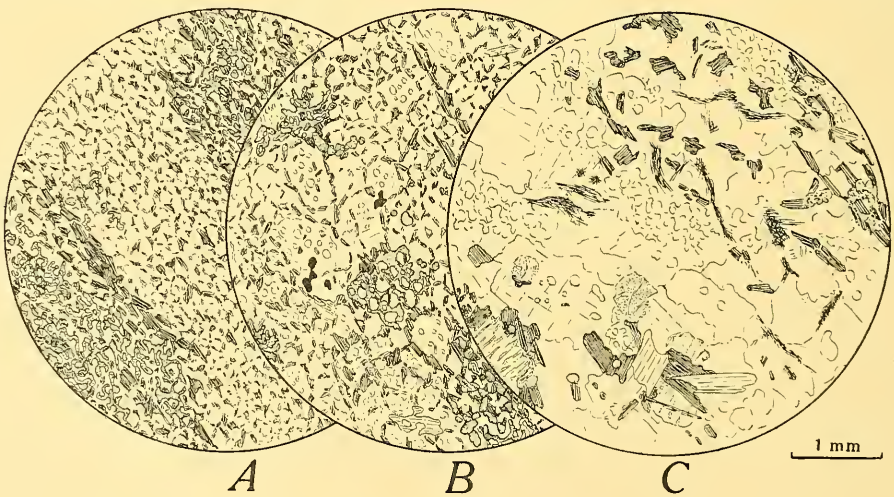

Fig. 8.

A. Corduroy granulite showing alternating bands. × 12.

B. Spotted granulite showing development of orthoclase porphyroblasts and breaking up of andalusite-biotite bands into a series of colinear spots. × 12.

C. Acid mottled gneiss showing sillimanite, muscovite and pinitized cordierite surrounded by grains of quartz and striated orthoclase. × 12.

colinear spots (Fig. 8B) or overlapping, elongated strips. The grainsize is now slightly coarser, the orthoclase porphyroblasts being from 0·5 to 1 mm. Muscovite is often abundant and occurs in large flakes, and apatite is sometimes present. In a few types a little cordierite occurs at this stage. These rocks may now be regarded as paragneisses.

Sillimanite makes its appearance at an advanced stage when original banding, though still recognizable in handspecimen, is represented only by colinear spots or overlapping and discontinuous rafts. In some types orthoclase appears to be giving place to muscovite and at this stage andesine may occur in the lighter bands. It was pointed out above that the presence of this mineral was suspected at an earlier stage. Myrmekite and striated orthoclase are now common and relict andalusite is present only in small amount. The sillimanite occurs in tufts or mats among the material of the original dark bands, but it also occurs in needles in quartz and muscovite. Cordierite is now well developed and may be subidioblastic against quartz, orthoclase or plagioclase. It is often much pinitized (Fig. 8C). The rock may now be regarded as a true mottled gneiss and in handspecimen most of these types are indistinguishable from those that have been derived from the aluminous pelites. Others, however, notably those from Mt. Gladstone, which were probably more siliceous types and showed a wider spacing of the pelitic bands, still preserve a slight banding that gives a clue to their origin.

(*b*) *Homogeneous Granulite Foundation.*—In the early stages of their development these rocks appear as dark grey granulites with a slight banding or flecking. Some types are slightly spotted and andalusite crystals stand out on weathered surfaces. At a later stage the types richer in pelitic material show the mottling characteristic of types derived from the aluminous pelite.

As there are all gradations between pelitic-rich and psammitic-rich psammopelites, there must be all gradations between the types of mottled gneiss derived from them.

Under the microscope the least altered types are contact-altered psammopelites with quartz, andalusite and reddish-brown biotite in varying amounts depending upon the rock's proximity to the pelitic or psammitic end-member. Some types are very slightly banded, but are included here as the banding is not apparent in handspecimen.

A type showing an early development of porphyroblastic orthoclase is from a small tributary on Slack's Creek, near the gate between Pors. 70 and 30, Parish of Binjura, at a distance of only a few yards from the normal silky knotted schist. This rock is very slightly banded and, as in the case of the corduroy granulites, the porphyroblasts develop first in the lighter bands. The more psammitic rocks still preserve a slight clastic structure at this stage of metamorphism (Harker, 1932). The detrital quartz grains are elongated, have sutured margins and show undulose extinction.

The more pelitic types are very similar to the mottled granulites at a corresponding stage of metamorphism. Small remnants of the original schist are now surrounded by a matrix consisting largely of quartz and orthoclase porphyroblasts, but, as in the case of the corduroy granulites, the development of sillimanite is somewhat retarded. Like the mottled granulites, these rocks may contain small segregations of the andalusite-quartz assemblage.

At a later stage cordierite, striated orthoclase, larger grains of quartz and often patches of myrmekite are present, but in the most advanced stage this type cannot be distinguished from the mottled gneiss derived from the pelite on the one hand, or from the corduroy granulite on the other.

(3) *Genesis of the Mottled Gneiss.*

(i) *Mineralogical Transformations.*

Although the corduroy granulites preserve their identity as banded sedimentary rocks long after the interbedded pelites are well on the way to becoming mottled gneisses, the changes taking place in all these rock groups are essentially similar and as such will be considered here.

The first mineralogical change is the development of orthoclase and large flakes of brownish-red biotite (presumably rich in haughtonite). This probably takes place without addition of material from the magma though it is no doubt promoted by magmatic accessions, and the selective penetration of these may explain the isolation of pelitic schist fragments, giving rise to the characteristic spots. In the banded psammo-pelites isolated colinear spots are developed by the same means.

Without addition of magmatic material, these newly-developed minerals possibly arise from the biotite thus:

$$2\{K_2O.3(Mg.Fe)O.Al_2O_3.8SiO_2.2H_2O\} = K_2O.6(Mg.Fe)O.Al_2O_3.6SiO_2.2H_2O + K_2O.Al_2O_3.6SiO_2 + 4SiO_2 + 2H_2O.$$

2 Biotite = Haughtonite + Orthoclase + 4 Quartz + 2 Water.

In the pelite the next stage after the initial budding-off of the schist fragments and the development of porphyroblastic orthoclase is the sillimanitization of much of the biotite. This change must be accompanied by the passing out of potash from the mica, which no doubt accounts for the shrunken and contorted appearance of the sillimanite pseudomorphs.

$$2\{K_2O.3(Mg.Fe)O.Al_2O_3.8SiO_2.2H_2O\} = K_2O.6(Mg.Fe)O.Al_2O_3.6SiO_2.2H_2O + Al_2O_3.SiO_2 + K_2O + 9SiO_2 + H_2O.$$

2 Biotite = Haughtonite + Sillimanite + Potash + 9 Quartz + Water.

The potassium, expressed here as an oxide, probably passes out as a hydrous silicate or possibly as a halogen compound. It probably attacks the andalusite closely associated with the biotite of the relict schist, and a further quantity of orthoclase or of muscovite is formed to bring about the disintegration of the schist fragment. These changes can be expressed by the following equations:

(1) $Al_2O_3.SiO_2 + K_2O + 5SiO_2 = K_2O.Al_2O_3.6SiO_2.$

Andalusite + Potash + 5 Silica = Orthoclase.

(2) $3\{Al_2O_3.SiO_2\} + K_2O + 3SiO_2 + 2H_2O = K_2O.3Al_2O_3.6SiO_2.2H_2O.$

3 Andalusite + Potash + 3 Silica + 2 Water = Muscovite.

At this stage volatiles from the magma play an important part in bringing about the partial mobilization of some of the endogenous material of the rock (Holmquist, 1922). Quartz and andalusite are dissolved under the influence of these emanations, and in the cavities so formed, the andalusite is re-deposited from a siliceous aqueous medium as large pink crystals. The quartz must remain in solution for a considerable time, for there is evidence that the large andalusite crystals were cracked and corroded before they were healed by the quartz, which occurs in small grains infilling cracks and cavities (Fig. 7F). This is rather similar to the corrosion and healing of large tourmaline crystals in pegmatites, a process which also probably takes place in the presence of volatiles.

At about this stage also, andalusite may give rise to sillimanite, and sometimes crystals of relict andalusite coalesce to form large porphyroblasts that occupy the site of the original schist remnants, and enclose only small grains of quartz and reddish-brown biotite.

Quartz and possibly orthoclase are now added from the magma, and at this stage also the original biotite and andalusite rapidly decrease in amount, with the formation of cordierite and muscovite.

$$2\{K_2O.3(Mg.Fe)O.Al_2O_3.8SiO_2.2H_2O\} + 10\,Al_2O_3.SiO_2 + SiO_2 = 2\{K_2O.3Al_2O_3.6SiO_2.2H_2O\} + 3\{2(Mg.Fe)O.2Al_2O_3.5SiO_2\}$$

2 Biotite + 10 Andalusite + Silica = 2 Muscovite + 3 Cordierite.

The coming in of albite-rich solutions with the formation of myrmekite and micro-perthite marks the final stages in the making over of the sedimentary rocks into the permeation or mottled gneiss.

(ii) *Chemical Discussion.*

In the foregoing section it is shown that the mineralogical changes, by which andalusite-bearing schists are converted into sillimanite-bearing paragneisses, may take place without addition of magmatic material, although they are no doubt promoted by igneous emanations. A slight magmatic addition, however, has been postulated to account for the passage from paragneiss to permeation-gneiss.

In Table 7 the analyses of three aluminous pelites, repeated from Table 3, are compared with those of four rocks from the permeation-zone. A casual glance will show that the gneisses have undoubtedly a pelitic foundation, but a direct comparison of the analyses is not satisfactory (Ransome, 1911; Browne and White, 1926; Joplin, 1933), nor can the analyses be compared on a basis of unit volumes since volume changes during metamorphism are unknown.

TABLE 7.

	I.	II.	III.	IV.	V.	VI.	VII.
SiO_2	54·18	58·87	56·40	54·63	56·05	59·05	61·13
Al_2O_3	25·48	21·23	23·20	25·35	24·91	22·95	23·43
Fe_2O_3	2·99	2·47	1·30	2·40	1·22	1·48	0·09
FeO	3·08	4·05	5·22	4·64	4·76	5·16	4·84
MgO	3·13	2·98	3·24	2·75	2·51	2·37	1·99
CaO	0·41	0·12	0·63	0·65	0·51	0·65	0·63
Na_2O	0·73	0·60	0·61	0·62	1·06	0·81	1·08
K_2O	5·70	5·73	5·65	6·28	6·12	5·85	5·84
H_2O+	2·88	2·59	2·77	1·25	1·23	1·17	0·26
H_2O-	0·48	0·22	0·30	0·26	0·22	0·18	0·20
TiO_2	0·73	0·84	0·57	0·86	0·86	0·68	0·72
P_2O_5	0·07	0·05	0·06	0·20	0·14	0·18	0·24
MnO	0·03	0·02	0·01	0·05	0·11	0·05	0·09
ZrO_2	n.d.	0·02	0·05	0·15	0·09	0·19	0·16
C	0·34	0·16	0·51	—	—	—	—
	100·23	99·95	100·52	100·09	99·79	99·86	100·70
Sp. Gr.	2·80	2·78	2·85	2·83	2·85	2·82	2·81

I. Chlorite-sericite-phyllite. Por. 144, Par. of Coolringdon. Anal. G. A. Joplin.
II. Plicated mica-schist (Fig. 2, IC). Crossing of Slack's Creek and Dry Plain Road. Anal. G. A. Joplin.
III. Knotted andalusite-schist (Fig. 2, ID). Por. 137, Par. of Binjura. Anal. G. A. Joplin.
IV. Spotted granulite (Fig. 7C). Por. 212, Par. of Binjura. Anal. G. A. Joplin.
V. Mottled gneiss. Spring Creek, Por. 212, Par. of Binjura. Anal. G. A. Joplin.
VI. Mottled gneiss. Spring Creek, Por. 212. Par. of Binjura. Anal. G. A. Joplin.
VII. Mottled gneiss. Mt. Gladstone, Por. 145, Par. of Jillamatong. Anal. G. A. Joplin.

In an attempt to ascertain what chemical changes have taken place, triangular diagrams have been constructed. In Fig. 9 normative orthoclase plus corundum (after satisfying alkalies and salic lime), albite and anorthite plus femic minerals are used as co-ordinates. This type of diagram has been employed by Brammall (1933) and MacGregor and Wilson (1939) to interpret chemical changes during granitization. It will be seen that the ungranitized schists (1, 2, 3) and the spotted granulite (4) show approximately the same amount of albite, but that the three mottled gneisses are offset towards the albite pole in the direction of the contaminated Cooma gneiss (8).

In trying to ascertain whether orthoclase has been added from the magma, it was necessary to know whether there was any variation in the orthoclase content of the original schist, or whether the range between 1 and 2 (Fig. 9) was due to a greater or less amount of corundum. Thus Fig. 10 was plotted with corundum and orthoclase as separate co-ordinates, and it will be seen that the original schists show sufficient range in orthoclase to account for any discrepancies between the mottled gneisses.

In Fig. 10 the muscovite-albite conjugation line separates the field of sediments (albite-corundum-muscovite) from that of igneous rocks (albite-orthoclase-muscovite). It will be seen that the mottled gneisses as compared with the ungranitized schists are slightly displaced towards the Cooma gneiss (8) in the igneous field.

To conclude, an examination of these diagrams shows that the paragneisses (5 and 6) are very slightly granitized by the addition of albite and that no orthoclase has been added from the magma. The permeation-gneiss (7) contains a little more albite, which has obviously come in as myrmekite or as part of the striated orthoclase, the latter having replaced the porphyroblastic orthoclase of the paragneiss.

Granitization by the incoming of soda rather than of potash solutions has been described by Goldschmidt (1920) from the Stavanger Region of Norway and by Read from Aberdeenshire (1927*a*) and from Sutherlandshire (1931), Scotland. In these areas the final product of granitization is an albite-porphyroblast-schist, but at Cooma, where the concentration of albite has not been so great, this highly sodic type does not occur.

In Norway and in Scotland the invading magma is trondhjemitic, but the Cooma gneiss, although soda becomes concentrated as an end-phase, is not initially a sodic type of magma.

It is of interest to note that zirconia is concentrated in the permeation-zone, and that the amount is comparable with that found in sodic alkaline rocks. It seems likely, therefore, that zirconia accompanied soda in permeating these rocks at some distance from the igneous body.

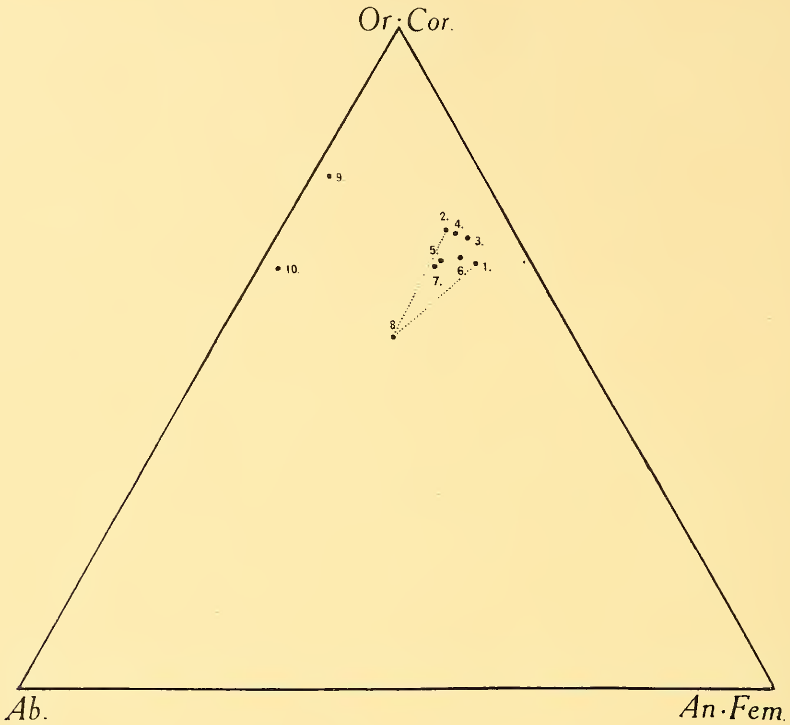

Fig. 9.

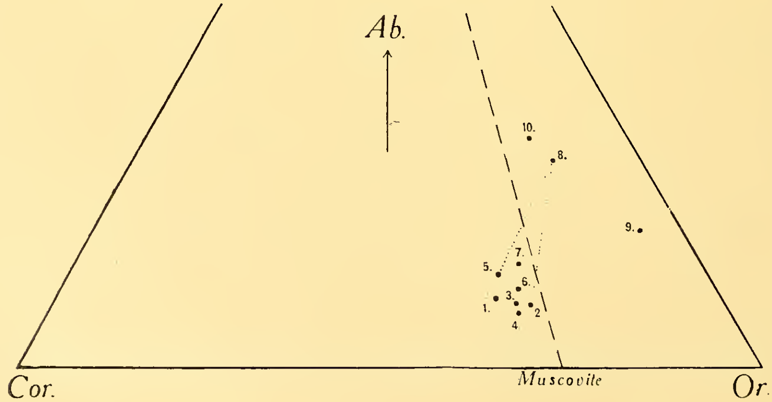

Fig. 10.

Figs. 9 and 10.—Normative variation diagrams showing plots of analyses, Table 9 (1-7) and Table 10 (1, 2, 4). Numbers of analyses 1-7 correspond with those of Table 9; 8, Cooma gneiss; 9, pegmatite; 10, albitized Cooma gneiss.

(4) *The Apparent Intrusive Relation of the Mottled Gneiss.*

In discussing the field occurrence of the mottled gneisses, it was pointed out that their relation to the associated corduroy granulite was usually concordant, but sometimes transgressive, and that it was for this reason that Dr. Browne regarded them as highly contaminated igneous rocks.

In the foregoing mineralogical and chemical discussions, it has been shown that most types of mottled gneiss may be derived from aluminous pelites or psammopelites without magmatic addition. The mottled gneisses are, therefore, mainly paragneisses, although mineralogical changes have probably been promoted by magmatic emanations acting as transporters and catalysers. The schistose pelitic rocks are more susceptible to this type of alteration and lose their identity before the more massive interbedded granulites, and thus appear as concordant intrusions among the banded rocks of undoubted sedimentary origin.

The change from corduroy granulite to mottled gneiss takes place rather irregularly, as there are no regular planes of weakness such as schistosity, and the junction between the granulite and the granulite-derived mottled gneiss may be somewhat irregular and rather similar to an intrusive junction. Occasionally the change from banded to mottled type may be traced in the field, and in every case the gneiss appears to transgress the banding of the granulite from which it is often separated by a wave-front of quartz or pegmatite. Thus the less common 'transgressive' mottled gneiss is most likely to be one derived from the corduroy granulite and the more common 'concordant' variety may be derived from the pelite or from certain psammopelites.

Furthermore, it has been shown that the action of volatiles may bring about limited mobilization of the sediments with the production of a quartz-andalusite assemblage. Although such patches of mobilized material are small and occur only in small veins and segregation patches, it is probable that under certain favourable conditions this plastic material may be slightly transgressive against the adjacent rocks. Finally, with the incoming of magmatic material in the permeation-gneisses this mobility may be somewhat increased.

2. INJECTION-ZONE (IGNEOUS MATERIAL DOMINANT).

(1) *Field Occurrence.*

The injection-zone is approximately 1½ miles in width and lies between the permeation-zone and the main outcrop of granite-gneiss. It consists mainly of injection-gneisses that exhibit good examples of *lit-par-lit* injection (Fig. 11). A small isolated occurrence at Pine Valley probably indicates an upward extension of the intrusion at this point.

On its outer margin the injection-zone grades into the permeation-zone, but in the former igneous material is more prominent, occurring in distinct tongues and small sills as well as in small discrete layers or patches in the injection-gneiss. The sedimentary host of the injection-gneiss may be pelitic, psammitic or psammopelitic. In the first case the rock is a mottled gneiss much threaded with granitic or pegmatitic material. Towards the injection body the rocks take on more distinctive characters and *lit-par-lit* injection is common. The sedimentary *lits* are themselves much granitized by soaking or permeation, as well as being interleaved with definite igneous material. In some cases these highly granitized schists are difficult to distinguish from the granite-gneiss, and on its inner margin the injection-zone passes almost imperceptibly into the latter, which contains numerous orientated inclusions of the granitized country-rocks.

(2) *Petrography.*

(i) *Sedimentary Host.*

(*a*) *Aluminous Pelite.*—In handspecimen these rocks show the characteristic mottling of the highly altered pelites, but in addition a gneissic banding is now developed by the discrete injection of granitic or pegmatitic material. The rocks are usually folded and the igneous tongues follow, and thus accentuate, these folds.

A small area of injection-gneiss occurs well away from the main zone among the permeation-gneisses in Pine Valley. This is probably due to an upward extension of the underlying intrusion, and the pegmatitic nature of the igneous *lits* tends to confirm the observation that the granite cupolas are of very acid composition (see p. 187).

The sedimentary bands of these rocks still show most of the characteristics of the permeation-gneiss, but very little relict andalusite now remains, and cordierite is entirely altered to pinite. The sedimentary *lits*, therefore, consist mainly of sillimanite, mica, quartz, and new andalusite and sometimes a little tourmaline introduced from the pegmatite.

Fig. 11.—*Lit-par-lit* injection. (Drawn from a photograph by W. R. Browne.)

Between Spring Creek and Snake Gully, on the outer border of the injection-zone, the rocks are still characteristically mottled gneisses, but no relict andalusite is present and there is a great development of the pink andalusite-quartz assemblage. On Snake Gully and well within the injection-zone to the east of it, sharply-defined gneissic banding is evident. The sedimentary bands, about 2 mm. in width, consist for the most part of matted strands and felts of sillimanite intergrown with or developing from biotite. Muscovite, intergrown with quartz, occurs in long bladed crystals up to 2·5 mm. in length and gives the rock a lepidoblastic structure.

The igneous *lits* consist of irregular grains of striated orthoclase up to 0·75 mm. in a fine base of quartz, muscovite and biotite. In types close to the igneous body the felspar is microperthite or highly myrmekitized orthoclase. Miniature folding is often well developed in these rocks, the igneous bands following the folds and the sedimentary ones frequently developing a false cleavage.

(*b*) *Psammopelites and Psammites.*—Psammopelites and psammites with an argillaceous matrix may be described together, as they differ only in the proportions of quartz present.

Many of these rocks show excellent examples of *lit-par-lit* injection, the igneous and sedimentary bands being quite distinct and sharp and showing beautiful examples of miniature folding. In handspecimen most of the rocks are fine-grained streaky grey and white gneisses, occasionally showing a slight augen structure. A few types, particularly the psammitic ones with macroscopic white mica, are more homogeneous and coarser in grain, and the igneous tongues thread through them irregularly.

It has already been pointed out that psammopelites are the commonest type in the Cooma district, so it is to be expected that the commonest variety of injection-gneiss has a psammopelitic host.

Under the microscope a gneissic banding is well shown and the mineral constitutions of sedimentary and igneous *lits* are quite distinct. In the sedimentary bands quartz grains are usually elongated and form a mosaic with biotite, muscovite and andalusite. Frayed knots of sillimanite sometimes occur, but andalusite is the stable aluminium silicate and when present sillimanite usually occurs as needles spearing muscovite and quartz. Cordierite is represented by masses of pinite. Sometimes larger units of quartz, andalusite and biotite are surrounded by a fine felt of tiny muscovite flakes, and in some types muscovite is present to the exclusion of any other alumino-silicate.

The igneous *lits* may be granitic or pegmatitic. When *lit-par-lit* injection is particularly well developed, it appears to be of a pegmatitic nature. These igneous bands vary from a few millimetres to more than fifteen millimetres in width, and consist of large irregular grains of microperthite or myrmekitized orthoclase, quartz with highly sutured boundaries, apatite and not infrequently tourmaline. Sometimes these pegmatitic tongues isolate tiny fragments of the sediment, which may be represented by large crystals of pink andalusite, by wisps of sillimanite, or by pinitized or sericitized grains of cordierite. When the granite-gneiss itself has been the agent of granitization, oligioclase occurs with irregular grains of quartz and a little orthoclase in the sedimentary *lits*.

(ii) *Igneous Host.*

The igneous rocks, of which there are three types among the country-rocks—basic granulites, amphibolites and chlorite amphibolites—do not form true injection-gneisses, although the first two have suffered a limited granitization.

It has already been stated (p. 171) that the basic granulites are sometimes injected by quartz-andesine veins and that large hornblende crystals have developed along their margins; but apart from this, no further granitization appears to have taken place, although the rocks actually occur as inclusions within the granite-gneiss.

The metasomatism of the normal amphibolites has been the subject of a separate investigation (Joplin, 1939). It was found that the original labradorite of the basic rock was partly replaced by silica and that at a slightly later stage there was further silicification accompanied by albitization and a simultaneous increase in the size of the hornblende crystals. Finally, these partly altered amphibolites were invaded by numerous quartz-andesine veins and, as in the case of the veins injecting the granulites, larger crystals of hornblende developed at their margins.

3. *The Granitization Process.*

Two types of granitization have taken place: (*a*) There has been a soaking in of magmatic fluids, which, though they deposited quartz and felspar, also brought about certain mineralogical changes within the country-rocks themselves, such as the formation of large andalusite crystals in the case of the sediments, and of large hornblende crystals in the case of some of the igneous rocks. (*b*) There has been an intimate penetration of discrete tongues of granite or pegmatite or *lit-par-lit* injection.

The first type has taken place in the permeation-zone remote from the igneous body, where dilute and highly mobile fluids have penetrated for considerable distances. The magmatic soaking of the country-rocks has been termed *permeation* by Read (1931) and others, and *imbibition* by the French petrologists (Lacroix, 1900).

The second type, involving the injection of magma and not of selective emanations, has taken place in the injection-zone immediately adjacent to the igneous body. This process, unlike the other, is not a soaking but a discrete injection.

Thus the magma itself has penetrated the heated and folded rocks only for a limited distance, approximately the width of the injection-zone, a distance of about 1½ miles, but certain selective fluids and alk-aluminous emanations may have migrated for as much as 3 miles from the main intrusive mass. The occurrence of small lenses of gneiss within the granitized zones indicates upward extensions of the intrusive body, so measurements on the width of the granitized zones can be only very approximate.

A study of the various phases of the Cooma gneiss indicates that the separation of pegmatite and the passing out of albite-rich solutions was a late episode in the differentiation of the magma, and as such solutions play an important part in the process of granitization, it may be assumed that granitization of the country-rock was a late stage in the history of the metamorphic complex. *Lit-par-lit* injection and ptygmatic folding indicate that temperatures were high and that some folding was possibly taking place at the time of granitization. According to Read (1931, p. 146) such conditions follow a tectonic maximum.

V. Ordovician Intrusives.

Within the area investigated ultrabasic, basic and acid intrusives occur, but intermediate types are notably absent. The main intrusion is a granite-gneiss with which pegmatites and other acid types are associated, and the basic and ultrabasic rocks occur as small bosses enclosed in the gneiss or invading the neighbouring granitized schists. The granite-gneiss is always contaminated by sedimentary material, and locally it has reacted with the basic type to form a hybrid.

For convenience the rocks will be described in the reverse order of their probable differentiation, thus the most acid, uncontaminated rocks will be dealt with first.

1. Cooma Gneiss and its Acid Phases.

(1) *Field Relations.*

In 1914, Dr. Browne mapped, and briefly described, a continuous outcrop of granite-gneiss about 5 miles in length and some 2½ miles in width. The town of Cooma is situated at about the centre of this mass, which Dr. Browne has called the Cooma gneiss. At the same time he recorded the occurrence of a number of small isolated lenses of gneiss among granitized schist to the north and to the west of the main outcrop. Since 1914, Dr. Browne has traced fairly continuous masses of Cooma gneiss invading granitized schist for a distance of about 14 miles north of Cooma, and he has been able to recognize large inclusions of it in the Silurian gneiss at a distance of some 30 miles north of Cooma. On p. 168 it was pointed out that the trend of the andalusite-zone at the northern end of the map (Plate v) indicates a northerly extension of the Cooma gneiss that has been engulfed by the Silurian intrusion.

Though termed a gneiss, the rock is more often massive, and the presence of numerous orientated xenoliths and large rafts of schist, where it merges into the injection-gneiss, tends to give a false impression of its gneissic character. In places, however, especially in the fine-grained mica-rich types occurring as isolated outcrops in the granitized schist, very definite directional structures are developed. Viewed macroscopically the grainsize of the rock is fairly even, but close examination shows the presence of small, often rounded, felspar phenocrysts. Sometimes large masses of quartz and felspar, over an inch in diameter, give the rock a very porphyritic appearance. It has been suggested that the quartz nodules represent undigested quartz veins which invaded the Ordovician sediments.

Xenoliths are very numerous in the gneiss, the larger ones almost invariably being orientated. Most types of the country-rock may be recognized among the inclusions, and, except for its most acid phases, the gneiss is always to some extent contaminated. In certain areas (indicated on the map, Plate v) basic granulites occur infrequently as xenoliths and often as flat pebbles scattered over the granite surface.

Small bosses of amphibolite occur as roof-pendants in the gneiss, and in their immediate vicinity the acid rock is basified.

On its western margin, Por. 161, Par. of Binjura, an acid felspathic phase of the gneiss is developed, and the isolated lenses of gneiss occurring among granitized schists are acid types rich in muscovite.

Large dykes of pegmatite are common in the Cooma gneiss and in the surrounding granitized zones. The positions of the principal dykes have been indicated by Browne (1914, Fig. 2). Small veins and tongues of pegmatite are very numerous in the injection-zone and sometimes occur in the permeation-zone. The large dykes are mostly parallel to the grain of the country and were possibly injected during a slight shearing stress.

Small quartz-felspar veins, showing no directional trends, were apparently injected as a late phase when compression had ceased.

(2) *Petrography.*

(i) *Acid Phases.*

(*a*) *Pegmatites.*—These rocks have been briefly described both by Dr. Browne (1914) and by myself (1939). On their outer margins most of the dykes consist of a coarse graphic intergrowth of quartz and felspar, which passes inwards into a felspar-rich zone with a rude comb structure. The centre of the dyke is infilled with quartz which may contain large crystals of tourmaline, muscovite and biotite.

Under the microscope the graphic border of a dyke from the quarry in Soho Street is seen to consist of quartz, microcline-microperthite, oligioclase and a little muscovite. The large felspars, about 10 mm. in diameter, are graphically intergrown with regular quartz units of about 3·5 mm. These units, however, are rarely single grains but consist of aggregates of small (0·4 mm.) grains, thus indicating a partial recrystallization of the rock. Further evidence of post-consolidation alteration is evidenced by the contortion of the microcline lamellae. The microcline contains fine threads of albite, and although this felspar appears in most instances to be late magmatic, the interruption of albite stringers by quartz inclusions suggests that some may have separated from solid solution. Some of the microperthite may therefore be pressure perthite (Browne, 1922), thus further corroborating the suggestion that the pegmatites were injected during a slight shearing stress. For the analysis of this rock see Table 8, Anal. III.

A very similar rock appears at Pine Valley, where it invades the chlorite amphibolite. This rock contains zoned crystals of tourmaline that have been cracked and corroded and subsequently healed by fine granular quartz. In this rock the potash felspar is partly replaced by muscovite, which may be due to magmatic greisenization or to shearing. The acid nature of the rock and the presence of tourmaline, together with the occasional radiating arrangement of the mica, suggests that it is at least partly magmatic.

(*b*) *Muscovite-rich Gneiss.*—These rocks usually occur as isolated outcrops among the granitized schists. They are markedly schistose and have a much finer grainsize than the normal Cooma gneiss, but in mineral constitution they may be identical with the greisenized normal gneiss.

They consist mainly of quartz, muscovite, often with a stellate arrangement, reddish biotite, altered orthoclase and usually some apatite and tourmaline. The orthoclase may be altered to white mica or to myrmekite.

(*c*) *Quartz-plagioclase Veins.*—These veins occur throughout the area of Cooma gneiss, but are especially noticeable and prominent when they intrude the basic rocks. They are well exposed in the amphibolite quarry in Soho Street and they have already been figured and briefly described from this locality (Joplin, 1939).

They consist only of three minerals—quartz, plagioclase and apatite. The plagioclase varies from andesine ($Ab_{64}An_{36}$) to oligioclase ($Ab_{72}An_{28}$).

(ii) *Contaminated Phases.*

(*a*) *The Normal Cooma Gneiss.*—The normal Cooma gneiss is never completely free from contamination. Two types occur among this gneiss, but as they differ only in that one contains porphyritic plagioclase in addition to porphyritic orthoclase, they will be described together. Good fresh exposures of the plagioclase-rich type are to be found in Massie Street, west of its intersection with Soho Street, and it would appear that the town is built mainly on the outcrop of this type, but as it occurs within the town area, its junction with the type less rich in plagioclase could not be mapped. Moreover, it is very difficult to distinguish the two types in the field.

In handspecimen most of these rocks are quite massive and of medium grainsize. They have a very characteristic appearance, the proportion of mica being unusually high for a rock so rich in quartz. They are light grey in colour, and small, somewhat rounded phenocrysts of felspar are common. Orientated rafts and narrow strip-like xenoliths of schist are abundant, and though their boundaries usually appear sharp in the hand-specimen, microscope examination reveals fairly extensive contamination of the magma.

A slightly gneissic structure and sometimes a schistosity is developed in these rocks and is most prominent in the plagioclase-poor types where orthoclase and muscovite are more abundant.

TABLE 8.

	I.	A.	II.	III.	IV.	B.
SiO_2	70·65	71·93	75·27	74·71	73·66	76·10
Al_2O_3	15·25	14·62	11·77	15·51	17·89	15·95
Fe_2O_3	0·83	0·83	1·95	tr.	tr.	tr.
FeO	3·45	2·25	2·91	tr.	tr.	n.d.
MgO	1·63	1·18	0·70	abs.	0·09	0·11
CaO	0·94	0·91	0·80	0·34	0·27	0·23
Na_2O	1·77	1·98	1·56	1·59	2·36	2·90
K_2O	4·63	5·03	3·08	8·11	5·12	3·27
H_2O+	0·60	0·75	0·70	0·10	0·58	1·16
H_2O-	0·09	0·34	0·15	0·03	0·07	
TiO_2	0·65	0·33	0·60	n.d.	n.d.	n.d.
P_2O_5	0·12	0·22	0·19	0·10	0·02	n.d.
MnO	0·05	0·03	0·05	abs.	tr.	n.d.
Etc.	—	0·02	0·10	—	—	—
	100·66	100·42	99·83	100·49	100·06	99·72
Sp. Gr.	2·79	—	2·74	2·60	2·67	2·673

I. Cooma gneiss (with plagioclase phenocrysts). Massie Street, Cooma. Anal. G. A. Joplin.
II. Gneiss. Cooma. Anal. H. B. Gurney, PROC. LINN. SOC. N.S.W., 34, 1909, 315.
III. Graphic pegmatite. Soho Street, Cooma. Anal. G. A. Joplin.
IV. Albite-muscovite-gneiss. Dry Plain Road, Por. 161, Par. of Binjura. Anal. G. A. Joplin.
A. Granite. Mt. Wagra, North-eastern Victoria. C. M. Tattam. *Geol. Surv. Vict.*, Bull. 52, 1929, 38.
B. Muscovite granite. Omeo, Victoria. A. W. Howitt, *Trans. Roy. Soc. Vict.*, 24, 1888, 110.

Under the microscope both types are seen to contain felspar phenocrysts in an allotriomorphic groundmass averaging about 1 mm. The phenocrysts are subidiomorphic crystals of plagioclase or irregular and somewhat rounded grains of orthoclase which may measure over 5 mm. The rocks consist of quartz, orthoclase, plagioclase and biotite with variable amounts of muscovite and myrmekite and accessory zircon, apatite and iron ore. Xenocrystal andalusite, sillimanite and biotite are usually present and, in addition, there is often a development of andalusite, and possibly of sillimanite, that has crystallized directly from the contaminated magma.

The orthoclase phenocrysts which are present in both types occur in large (about 5 mm.) somewhat rounded irregular grains. They are often fringed by encroaching areas of myrmekite, which may also occur along cracks and completely replace the potash felspar. In these extreme cases the released potash is deposited as muscovite, which is found in close association with the myrmekite along cracks.

Plagioclase is an oligioclase-andesine ($Ab_{65}An_{35}$ to $Ab_{63}An_{37}$) and occurs both as large tabular phenocrysts and as small clear grains in the allotriomorphic groundmass. The phenocrysts usually show mottling and sometimes a peculiar checking which seems to have been caused by the envelopment of groups of small rectangular felspar by later material. Many of the larger plagioclase crystals contain minute needles of muscovite arranged in one or more directions, usually parallel to cleavages. Some crystals show strain.

Quartz is very abundant both as small irregular grains (0·1 mm.) between the felspar phenocrysts and as large irregular grains (1 mm.) in the more even-grained varieties of the rock.

Large irregular and corroded crystals of pink, pleochroic andalusite are closely associated with mats of sillimanite, muscovite and xenocrystal biotite. Sometimes remnants of this paragenesis are suggestive of the schist remnants in the mottled gneiss and are indeed the last fragments of the aluminous pelite to have escaped complete resorption by the magma. Much of the andalusite appears to be magmatic and may have recrystallized directly from the gneissic magma. Some may represent fragments of the andalusite-quartz segregations from the schists that would be stable under magmatic conditions.

Muscovite is abundant in some types, particularly in the rocks rich in orthoclase and poorer in plagioclase. The large flakes are usually speared by needles of sillimanite. Small flakes of secondary origin occur with myrmekite and quartz along cracks and crush zones where alteration has taken place.

Apatite occurs in rare stout crystals, and small zircons are often present as inclusions in the biotite.

A specimen free from macroscopic xenoliths was chosen for analysis. This represents a type containing both plagioclase and orthoclase phenocrysts, and it is interesting to note the similarity between this and a granite from North-Eastern Victoria (Table 8, Anals. I and A).

(*b*) *Altered Types of the Normal Gneiss.*—Two types of alteration occur—greisenization and albitization. In describing the normal rock, it was pointed out that the orthoclase was very susceptible to myrmekitization and that the released potash was deposited as muscovite. Many of the rocks show an advanced stage of this type of alteration and only cores of the original orthoclase may remain to indicate that the rock was once a normal type, poor in plagioclase.

In some cases the rock appears only to have been greisenized, and such types are difficult to distinguish from highly acid rocks that have crystallized directly from the magma.

Another type whose origin is in doubt is rich in albite (Table 8, Anal. IV). It may have crystallized directly from a magma which has been squeezed out to the west, or what seems more probable, it may represent the almost complete alteration of the normal gneiss. The rock occurs on the western margin of the gneiss on the Dry Plain Road. The outcrop is not extensive and a small cutting at the roadside reveals a light cream-coloured rock consisting mainly of quartz and felspar. In certain bands, however, very large idiomorphic crystals of biotite and of muscovite are developed, and there is some muscovite in the main body of the rock.

Under the microscope the rock is allotriomorphic granular with a fairly even grainsize of about 3 mm. Albite ($Ab_{97}An_3$) surrounds cores of kaolinized and sericitized material which was possibly original orthoclase. Quartz is very abundant in irregular grains, and muscovite is abundant in patches and almost absent in others, thus suggesting a somewhat irregular alteration of the original rock.

(iii) *Hybrid Phases.*

In handspecimen these rocks appear as highly micaceous granites or gneisses studded with small white felspar phenocrysts, and, except for their darker colour and greater abundance of mica, are rather similar to the typical Cooma gneiss, from which they have been derived. They occur in the Soho Street quarry in the immediate vicinity of the amphibolite, and with a decrease in their mica content merge imperceptibly into the normal plagioclase-rich gneiss.

Under the microscope two hybrids may be distinguished, an amphibolite-gneiss hybrid and an amphibolite-pegmatite hybrid. The first consists of biotite, quartz and oligioclase-andesine ($Ab_{75}An_{25}$–$Ab_{63}An_{37}$). The felspar occurs as phenocrysts up to 3 mm. and may form irregular grains or subidiomorphic tabular crystals. Zoning and blotching are characteristic and the mineral is usually sericitized. Biotite, a dark sepia variety, occurs in irregular flakes, and quartz has highly sutured boundaries. The amphibolite-pegmatite hybrid contains microcline in addition to the above minerals and in this case plagioclase is poorly developed. The microcline, showing well-developed spindle-shaped lamellae and often a development of both microperthite and myrmekite, occurs in large (7 mm.) irregular grains in a quartz-biotite base averaging 0·1 mm.

(iv) *Xenoliths.*

Most types of the country-rock may be identified among the xenoliths in the Cooma gneiss. These vary from large rafts several feet in length to small masses less than an inch in diameter.

It is not proposed to make a complete study of these inclusions here, but merely to record the types that have been so far recognized.

Xenoliths of aluminous pelite and of psammopelite with an argillaceous matrix are the commonest types. These are similar to the sedimentary bands of the injection-gneisses where it was noted that (*a*) biotite was giving rise to sillimanite, (*b*) biotite and sillimanite to pink pleochroic andalusite and (*c*) cordierite to pinite. It seems evident that the stable assemblage is andalusite and red-brown biotite and that all these other minerals are in unstable equilibrium.

When in an advanced stage of resorption, irregular grains of plagioclase are developed in the xenolith. Original bedding is still preserved in the case of the banded psammopelites.

Only one specimen of the psammopelite with a tuffaceous matrix is recorded. It was found as a large block among split boulders of Cooma gneiss in Massie Street, and presumably occurred as an inclusion. The rock consists of quartz, basic plagioclase, brown mica and an occasional irregular porphyroblast of pink garnet. Apatite is prominent and a well-marked schistosity is developed.

It is believed that the hornblende-pyroxene-granulites described on pp. 171–2 are igneous xenoliths that have been weathered out from the Cooma gneiss. A few that have been found enclosed in their host are identical with these.

2. BASIC AND ULTRABASIC INTRUSIVES.

(1) *Field Occurrence.*

These rocks occur in small irregular or somewhat circular masses either within the granitized zones or within the granite-gneiss. The basic type is represented by amphibolites that were described in an earlier communication (Joplin, 1939). The ultrabasic type is a chlorite-amphibolite.

Although a note on the amphibolites has already been published, they are included here for two reasons. First, they are probably co-magmatic with the Cooma gneiss, and secondly, it is necessary to record another occurrence which was not discovered until after the publication of the other paper. This rock is identical with the other amphibolites and like them occurs within the Cooma gneiss. The outcrop occupied an area of 20 × 30 yards on the western side of Cooma Creek gorge in the Temporary Common immediately west of Por. 123, Parish of Cooma.

The main mass of the chlorite-amphibolite crops out at Pine Valley in Por. 70, Parish of Binjura and occupies an area of 20 × 15 yards. It is completely surrounded by granitized schists, but has itself escaped granitization. Another very small mass has been found as an inclusion in the gneiss on the northern bank of Cooma Creek just before it turns north into the gorge. Possibly other such inclusions exist.

(2) *Petrography.*

(i) *Amphibolites.*

It has been shown that amphibolites consisting almost exclusively of hornblende and basic labradorite have been granitized by the addition of quartz and albite. Several analyses have been made of these rocks (Joplin, 1939).

(ii) *Chlorite-Amphibolites.*

These rocks have a very simple mineral composition and consist of amphibole, chlorite, a little iron ore and sometimes a trace of apatite. One type contains a little diopside. It is of interest to note that ultrabasic rocks of very similar constitution occur in the Lewisian of Sutherland (Read, 1931, p. 78).

In the handspecimen the rocks are light brownish-green, very tough, without directional structures. Their texture varies from medium to fairly coarse, and under the microscope it is obvious that the difference in texture is due mainly to the different size and arrangement of the amphibole crystals.

Chlorite is always interstitial and occurs in large flakes (about 3 mm. across) or in radiating masses of bladed crystals (1·5 mm. in length) that form patches about 3 mm. across. The mineral is pale green with a birefringence of 0·007, $\alpha' = 1{\cdot}585$, it is optically positive with a small optic axial angle. According to Winchell (1927) it is, therefore, a type rich in alumina. Probably the whole of the alumina of the rock is contained in this mineral.

The amphibole occurs in individual crystals about 1·5 mm. in length or, in the fine-grained types, as felted masses of small (0·5 mm.) crystals. It appears to consist mainly of tremolite, but the composition varies within a single crystal, the core often being bluish-green and clouded with brownish material which suggests very finely-divided sphene. The outer rim of the amphibole crystal is completely colourless and from this border there may be little outgrowths of minute anisotropic needles whose optical properties are difficult to determine: in view of the high magnesia content of the rock (Table 9, Anal. I) these may be anthophyllite.

TABLE 9.

	I.	A.	B.	C.	D.	E.
SiO_2	46·36	43·24	46·20	45·63	43·70	46·40
Al_2O_3	10·38	7·97	9·16	8·83	11·20	10·80
Fe_2O_3	5·68	1·68	1·77	4·79	3·90	5·90
FeO	3·24	8·22	4·13	5·92	6·15	5·60
MgO	24·69	24·72	28·67	20·30	25·60	22·20
CaO	5·08	5·15	7·13	7·83	7·07	3·72
Na_2O	0·46	0·17	0·40	0·63	0·52	0·30
K_2O	0·05	0·02	abs.	0·34	0·31	1·21
H_2O+	3·39	6·97	2·48	4·23	} 2·80	3·85
H_2O-	0·19	0·04	0·24	0·14		
TiO_2	0·22	0·52	—	1·44	—	—
P_2O_5	0·03	0·14	tr.	—	—	—
MnO	0·42	0·16	tr.	—	—	—
CO_2	—	1·44	—	—	—	—
	100·19	100·44	100·18	100·10	101·25	100·18
Sp. Gr.	2·95	2·94	2·90	3·05	—	—

I. Chlorite-amphibolite. Pine Valley, Por. 70, Par. of Binjura, Cooma. Anal. G. A. Joplin.
A. Actinolite amphibolite partially chloritized. Schuyler Soapstone Quarry, Virginia, U.S.A. Anal. R. B. Ellestad. H. H. Hess. *Amer. J. Sci.*, 26, 1933, 382.
B. Serpentine rock. Rockwell Intrusion, Broken Hill. Anal. J. C. H. Mingaye. W. R. Browne, *Geol. Surv. N.S.W.*, Mem. 8, Appendix 1, 1922, 47.
C. Hornblendite. Clemgia, Lower Engadine, Switzerland. Anal. L. Hezner. V. Grubenmann, *Btr. G. Kt. Schw.*, 1909, 23, 223. In W.T. No. 1, p. 721.
D. Hornblende-bronzite peridotite. Bord de l'étang de l'Estagnet, Pyrénées. Anal. A. Pisani. A. Lacroix, *Carte Geol. France*, Bull. 11, 1900, 31.
E. Micaceous hornblendite. Valée de Valbonne, Pyrénées. Anal. A. Pisani. Ibid.

Iron ore is very poorly developed and its skeletal growth suggests ilmenite. Apatite occurs sporadically, but is never abundant, and diopside has been detected only in one rock from Pine Valley.

A type occurring as an inclusion in the gneiss on Cooma Creek contains large crystals of amphibole in which sharply-defined rectangular patches of colourless amphibole occur. These are usually surrounded by minute grains of magnetite, the colourless amphibole is optically continuous with the amphibole host, and it seems likely that the colourless patches represent pseudomorphs after pyroxene.

Although these rocks occur within the granitized-zone or within the gneiss itself, there is no evidence of granitization.

(3) *Nature of the Original Plutonic Rocks.*

It has already been shown (Joplin, 1939) that the amphibolites were probably norites or olivine-gabbros. Four analyses of these rocks are plotted on the A-F-C diagram (Fig. 5), and it will be seen that they fall on the opposite side of the cordierite-diopside conjugation-line from the basic granulites. These evidently represent a different magma-type from that which gave rise to the basic flows.

The field occurrence and chemical composition of the chlorite-amphibolites indicate that they are probably small basic intrusions. It was suggested (Joplin, 1939) that they might represent gabbros that have suffered dynamic metamorphism, but it is now obvious that they belong to a more basic group which, however, may be magmatically related to the normal amphibolites.

In Table 9 the analysis of a chlorite-amphibolite is compared with analyses of ultrabasic rocks, several of which occur in close association with injection-complexes (Lacroix, 1900; Browne, 1922). The serpentine from the Rockwell intrusion of Broken Hill is chemically comparable, but mineralogically dissimilar to the Cooma rock. Jaquet (1894) has described amphibolites from another part of the Broken Hill district, which compare mineralogically with, but differ chemically from, the Rockwell serpentine. Dr. Browne has lent me slides of rocks from another part of the Rockwell intrusion, however, which are almost identical with the Cooma rock, and it would be interesting to know if they compare with the serpentine in chemical composition.

As both basic and ultrabasic intrusions invade Upper Ordovician sediments and are themselves altered by the late Ordovician granite-gneiss, it is likely that they are co-magmatic with the gneiss.

3. Magmatic History.

(1) *Differentiation.*

It has been shown that ultrabasic and basic intrusions preceded the injection of the Cooma gneiss, and that these probably invaded the schists after their first stamp of metamorphism when stress was waning or no longer operating. As the schists are of Upper Ordovician age and Browne (1929) considers that the granite-gneiss was probably intruded at the close of the Ordovician, it is likely that the ultrabasic and basic rocks are magmatically related to the Cooma gneiss. Further, it has been shown that the gneiss always shows evidence of assimilation and that only its acid and more alkaline end-phases are free from such phenomena.

The association of basic and acid rocks and the absence of intermediate types has been noted in most metamorphic complexes, but a completely satisfactory explanation is not forthcoming. In trying to account for such an association, especially the association of dolerite and granophyre and of quartz-dolerite and micropegmatite in younger rocks, Nockolds (1934, 1936) and Holmes (1936, 1937) have both discussed "the idea of contrasted differentiation", the former holding that it is due to differentiation and the separation of an acid residuum, the latter invoking the aid of assimilation and the action of magmatic emanations.

Nockolds would account for the production of intermediate rock-types by interaction between the two extreme differentiates after contrasted differentiation had taken place. If such an explanation were accepted, it would not be difficult to account for the absence of intermediate rocks among the old folded complexes, where compressional forces might have been responsible for squeezing out the acid liquid fraction and so separating the two contrasted differentiates before hybridization could take place.

On the other hand, it may be significant that the Cooma gneiss is a contaminated rock. Whether this is a genetic characteristic or whether it is merely an accidental feature due to the picking up of material by a separate acid magma or partial magma, it is at present impossible to say. Holmes (1937) considers that the assimilation of the country-rock is brought about by fusion and transfusion, and so far as Cooma is concerned, evidence of transfusion, of the operation of magmatic emanations and of the presence of a felspathic residuum is by no means lacking.

Whatever the origin of the acid magma may be, however, there is little doubt that differentiation accounted for the various late acid and somewhat alkaline phases.

The relative age of the two types of normal gneiss is unknown. The plagioclase variety, occurring in the town, appears to be entirely surrounded by the other type, and field relations are difficult to determine. On the evidence of other magmatic-series, particularly of those having trondhjemitic affinities, the normal sequence seems to be the crystallization of a micaceous variety and the storing up of soda in the magma, followed by the precipitation of this soda in a late plagioclase-rich phase.

The pegmatites invade the gneiss and there is evidence that they were intruded before compression had entirely ceased. These are albitized and the occurrence of an albitized phase on the western margin of the normal gneiss, as well as the presence of albite in the granitized schist to the west, suggests a squeezing out of soda solutions during the final decline of stress. The injection of small veins of quartz-andesine composition during a time of tension (Joplin, 1939) marks the last phase of differentiation. Thus there have been two fluctuations in the potash and soda concentrations of the magma during its final cooling history.

(2) *Assimilation.*

Contamination is a characteristic of the Cooma gneiss. From a study of the granitized aluminous pelites it is obvious that the andalusite-quartz-biotite assemblage is the stable one under magmatic conditions. Although sillimanite and other xenocrystal material sometimes occurs in the granite-gness, it is in unstable equilibrium.

Hybridization is of limited occurrence in the vicinity of the amphibolite. The original plagioclase of the basic rock has been completely silicified or converted into oligioclase-andesine, and potash from the acid magma has converted original hornblende into sepia biotite. In the case of the amphibolite-pegmatite hybrid, there has been sufficient potash available to deposit microcline as well.

VI. Metamorphic Unconformity.

In the Highlands of Scotland the normal sequence of regional metamorphism includes an almandine and a cyanite zone between the biotite and sillimanite zones. These are missing at Cooma.

It has been shown that the sillimanite-zone is included within that area mapped as the permeation-zone, but that a contact-zone in which andalusite is the stable aluminium silicate, is also present. Andalusite does not appear in the normal Highland sequence, and when it occurs with cordierite elsewhere, as in Banffshire and Aberdeenshire, Harker (1932) regards it as indicative of a deficient shearing stress. Moreover, he considers that both almandine and cyanite are stress minerals. Their absence at Cooma, coupled with the presence of andalusite, indicate that stress conditions never reached a maximum. The presence of biotite in rocks still showing a clastic structure is regarded by Harker as a further indication that temperatures were high and stress comparatively low. Conditions at Cooma, however, were not typically those of normal thermal metamorphism, hence a contact-zone was developed about the gneiss, and though no true hornfelses occur and the earlier schistosity is still preserved, such high temperature minerals as andalusite and cordierite are developed.

In discussing the distinctions between the synchronous and subsequent bathyliths (Billings, 1928; Browne, 1931*a*) have enumerated certain characteristics of each. Except for the presence of its thermal aureole, Cooma typifies the first and this slight deviation from type may mean that the Ordovician movements were not of such intensity as those of Pre-Cambrian time and that there was a deficiency of shearing stress.

The relation of the zones of regional metamorphism to those of granitization and to the injection body is obscure. The southerly extension of the metamorphic zones is unfortunately overlain by basalts, but except for local irregularities in the Parishes of Jillamatong and Murrumbucka their boundaries appear to be parallel to the contact-aureole of the gneiss. Furthermore, the time interval between the formation of the lower grade schists and that of the granitized schists could not have been very great, for Upper Ordovician graptolites are found in the less altered rocks, and on the east the granitized rocks appear to be overlain by Upper Silurian Beds. From this it has been deduced (Browne, 1929) that the Cooma gneiss was intruded before Upper Silurian Time and probably at the close of the Ordovician. The relation between the lower grade zones and the granitized sillimanite-zone, therefore, brings up the vexed question of the relation between regional metamorphism and igneous intrusion.

Daubré (1862) first employed the term 'regional', but recognized the association of gneisses with the crystalline schists, and later Rosenbusch (1910) and others regarded regional metamorphism as identical with dynamic metamorphism, and any association of igneous material was thought to be fortuitous. After reviewing the various definitions of metamorphism, Daly (1917) defined regional as a type not associated with igneous intrusion as opposed to contact metamorphism which is associated. Tilley (1925) and Harker (1932) are of the same opinion, yet Barrow (1883), in first distinguishing the zones which are now accepted as the normal sequence of regional metamorphism, regarded them as gigantic contact-aureoles about the Older granites of the Scottish Highlands. Read (1940) has recently discussed the question and although he will admit only that regional can mean metamorphism of a great regional tract of country, he leans towards the earlier view of Barrow.

In the type localities of the Scottish Highlands the sillimanite-zone is injected by granite-gneiss and much granitized by pegmatitic material. Those who would dissociate regional metamorphism from igneous intrusion regard these masses of Older granite as incidents consequential upon the deep burial of the sillimanite-zone, and it is difficult to refute this argument, unless it can be shown that grade of metamorphism is not a function of depth, that the zones are concentric about the gneiss or that the sillimanite-zone is in part the result of granitization.

Read (1940), quoting various British examples, regards the sillimanite-zone as intimately related to migmatic injection, and thus argues in favour of the association of regional metamorphism and igneous injection.

So far as Cooma is concerned, the permeation-zone is essentially similar to the sillimanite-zone of the Highlands, except that cordierite and andalusite are also present.

VII. Tectonic and Magmatic History.

There is no doubt that the granitized zones and the andalusite- or thermal-zone together form a contact-aureole about the Cooma gneiss, but the relation of the biotite and chlorite zones to the igneous mass is somewhat obscure. There is evidence that contact metamorphism has been superimposed upon the earlier schistosity, indicating a time lapse between the two types of metamorphism, but they obviously belong to the same diastrophic epoch, as the schists are of Upper Ordovician age and the granite-gneiss is pre-Upper Silurian.

This period of diastrophism seems to have been ushered in by the folding of the country-rocks under conditions of medium compression and shearing stress. Chlorite and biotite schists were thereby formed, but shearing stress was not great enough to raise them beyond the biotite-grade.

Compression and shearing stress then declined and ultrabasic and basic magmas invaded the schists. These were followed by a slow upward movement of acid magma (Cooma gneiss), and the schists were raised to a high temperature. Contact metamorphism was thus superimposed upon the schists. This was strong enough to produce mineralogical changes such as the development of andalusite and cordierite, but not strong enough to stamp out the earlier schistosity and give rise to hornfels-structures.

The upward movement of the acid magma continued now with *strong local compression*. The temperature was at a maximum, and in the immediate vicinity of the uprising magma the schists were raised to the sillimanite-zone. The magma was emplaced under a force strong enough to produce some primary gneissic banding, *lit-par-lit* injection and the rifting off of orientated xenoliths.

In discussing the differentiation of the Cooma gneiss magma, two fluctuations in the potash and soda concentrations were noted, but it is difficult to say which soda-maximum was responsible for the albitization and granitization of the schists within the permeation-zone. If the first albite concentrate was responsible, permeation probably took place slightly in advance of the emplacement of the magma and before the formation of the injection-zone. If the second albite concentrate was the one responsible for the permeation, then this took place after the separation of the pegmatite and the formation of the injection-zone. The second phase of albitization seems to be the more likely.

A waning of compression seems to have followed the emplacement of the gneiss and *lit-par-lit* injection, for the gneiss is usually massive, but the orientation of the larger pegmatite dykes and their internal evidence of post-consolidation stress suggest a slight renewal of compressional force. The permeation-gneisses were probably formed at about this time. Finally, the quartz-plagioclase veins were injected during a time of tension.

VIII. Summary.

It has been shown that the Ordovician rocks at Cooma may be divided into two units—the upper or Coolringdon Beds consisting of sandstones and siliceous slates, and

the lower or Binjura Beds which consisted originally of sandstones, aluminous shales, tuffaceous sandstones and small basalt flows. The Binjura Beds have been invaded by small ultrabasic and basic masses and finally by a mass of granite-gneiss which has been responsible for their partial granitization.

Various zones of metamorphism have been traced in the non-granitized country-rocks and two granitized zones, an outer permeation-zone and an inner injection-zone, may be recognized.

Finally, the magmatic and tectonic histories of the area have been briefly discussed.

IX. *Acknowledgements.*

In conclusion, I should like to express my gratitude to Dr. W. R. Browne, who not only introduced me to this interesting area, but who has also made available his note books, specimens, slides and unpublished maps and his great fund of knowledge and experience in this region. Moreover, his stimulating discussion and kindly criticism have proved invaluable in the preparation of this manuscript.

For hospitality and help during field work, I gratefully acknowledge the kindness of Mr. and Mrs. A. Sherlock and Miss N. Sherlock of Kiaora, and of Mr. Hain and family of Arable.

This work was commenced with financial assistance from the Commonwealth Research Fund administered by the University of Sydney.

X. *References.*

Bailey, E. B., Thomas, H. H., *et al.*, 1924.—Tertiary and Post-Tertiary Geology of Mull. *Mem. Geol. Surv. Scot.*, 23-25.

Barrow, G., 1893.—On an Intrusion of Muscovite-Biotite Gneiss in the South-Eastern Highland of Scotland, and its Accompanying Metamorphism. *Quart. J. Geol. Soc. Lond.*, 49, 343.

————, 1912.—On the Geology of Lower Deeside and the Southern Highland Border. *Proc. Geol. Ass. Lond.*, 23, 274-279.

———— and Craig, E. M. Cunningham, 1912.—The Geology of the Districts of Braemar, Ballater and Glen Clova. *Mem. Geol. Surv. Scot.*, 65, 13-24.

Barth, T. F. W., 1926.—Structural and Petrographic Studies in Dutchess Co., N.Y. *Bull. Geol. Soc. Amer.*, 47, 775-850.

Billings, M., 1928.—The Petrology of the North Conway Quadrangle in the White Mountains of New Hampshire. *Proc. Amer. Acad. Arts Sci.*, 63, 91.

Brammall, A., 1933.—Syntexis and Differentiation. *Geol. Mag., Lond.*, 70, 101.

Browne, W. R., 1914.—The Geology of the Cooma District, N.S.W. *J. Roy. Soc. N.S.W.*, 48, 172-222.

————, 1922.—Report of the Petrology of the Broken Hill Region, excluding the Great Lode and its Immediate Vicinity. *Mem. Geol. Surv. N.S.W.*, 8, App. 1, 47.

————, 1929.—An Outline of the History of Igneous Action in N.S.W. till the Close of the Palaeozoic Era. Pres. Address, Proc. Linn. Soc. N.S.W., 54, xiii, xvi.

————, 1931*a*.—Notes on Bathyliths and Some of their Implications. *J. Roy. Soc. N.S.W.*, 65, 114-116.

————, 1931*b*.—Exhibits. Abstract of the Proceedings of the Geological Section. Ibid., 65, li.

———— and White, H. P., 1926.—The Hypersthene-Andesite of Blair Duguid, near Allandale, N.S.W. Ibid., 60, 380.

Clarke, F. W., 1916.—The Data of Geochemistry. *Bull. U.S. Geol. Surv.*, No. 616, 545-548.

Daly, R., 1917.—Metamorphism and its Phases. *Bull. Geol. Soc. Amer.*, 28, 394, 409.

Daubrée, M., 1862.—Études sur le Métamorphisme. *Mém. Acad. Sci. Paris*, 17, 59.

Eskola, P. P., 1920.—The Mineral Facies of Rocks. *Norsk. geol. Tidsskr.*, 6 (1-2), 156-7.

Goldschmidt, V. M., 1911.—Die Kontaktmetamorphose im Kristianiagebiet. *Videnskaps-Selskap. Skrifter. I Mat.-naturv. Klasse*, 1911, No. 1, p. 146, Pl. i, fig. 1.

————, 1920.—Geologisch-Petrographhische Studien im Hochgebirge des Südlichen Norwegens. v. Die Injektionsmetamorphose im Stavanger-Gebiete. Ibid., 1920, No. 10, p. 81.

Harker, A., 1932.—Metamorphism. London, 208-218, 230, 244.

Holmes, A., 1920.—The Nomenclature of Petrology. London, 35, 212.

————, 1936.—The Idea of Contrasted Differentiation. *Geol. Mag. Lond.*, 73, 228-38.

————, 1937.—Id. Ibid., 74, 189-191.

Holmquist, P. J., 1922.—Typen und Nomenklatur des Adergesteine. *Geol. Fören. Stockh. Förh.*, 43, 626.

Hutchings, W. M., 1892.—Ash-slates and Other Rocks of the Lake District. *Geol. Mag. Lond.*, 9, 154.

Hutton, C. O., 1940.—Metamorphism in the Lake Wakatipu Region, Western Otago, New Zealand. *Dept. Sci. Industr. Res. N.Z.*, Geol. Mem., 5, 30.

Jaquet, J. B., 1894.—Geology of the Broken Hill Lode and Barrier Ranges Mineral Field, N.S.W. *Geol. Surv. N.S.W.*, Geol. Mem. 5.

JOPLIN, G. A., 1933.—The Petrology of the Hartley District. II. The Metamorphosed Gabbros and Associated Hybrid and Contaminated Rocks. PROC. LINN. SOC. N.S.W., 58, 150.

————, 1935.—Id. III. The Contact Metamorphism of the Upper Devonian (Lambian) Series. Ibid., 60, 48.

————, 1939.—Studies in Metamorphism and Assimilation in the Cooma District of N.S.W. Part I. The Amphibolites and Their Metasomatism. *J. Roy. Soc. N.S.W.*, 73, 86-106.

LACROIX, A., 1898-99.—Le Granite des Pyrénées et ses Phénomènes de Contact. *Carte Geol. Fr.*, 10, No. 64, 8-9.

————, 1900.—Id. Ibid., 11, No. 71, 31-2.

MACGREGOR, M., and WILSON, G., 1939.—On Granitization and Assimilation Processes. *Geol. Mag. Lond.*, 76, 196, 207.

NOCKOLDS, S. R., 1934.—The Production of Normal Rock Types by Contamination and Their Bearing on Petrogenesis. Ibid., 71, 31-39.

————, 1936.—The Idea of Contrasted Differentiation: A Reply. Ibid., 73, 529-535.

RANSOME, F. L., 1911.—The Geology of Ore Deposits of the Breckenridge District, Colorado. *U.S. Geol. Surv.*, Prof. Paper, 75, 96.

READ, H. H., 1927*a*.—The Igneous and Metamorphic History of Cromar, Deeside, Aberdeenshire. *Trans. Roy. Soc. Edinb.*, 55, 321, 342-3.

————, 1927*b*.—A Note on Ptygmatic Folding in the Sutherland Granite-Complex. *Geol. Surv. Grt. Brit. Summ. Prog.*, Pt. II, 72.

————, 1931.—The Geology of Central Sutherland. *Mem. Geol. Surv. Scot.*, p. 78, p. 119.

————, 1940.—Metamorphism and Igneous Action. *Brit. Ass. Adv. Sci.*, Pres. Address, Section C, 244, 250.

———— and PHEMISTER, J., 1925.—The Geology of the Country around Golspie, Sutherland. *Mem. Geol. Surv. Scot.*, p. 4, p. 5, p. 7.

ROSENBUSCH, H., 1910.—Elemente der Gesteinslehre. Stuttgart, 73.

SEDERHOLM, J. J., 1907.—On Granite and Gneiss, their Origin, Relation and Occurrence in the Pre-Cambrian Complex of Fenno-Scandia. *Bull. Comm. géol. Finl.*, 5, No. 23, p. 101.

————, 1916.—On Synantetic Minerals and Related Phenomena. *Bull. Comm. géol. Finl.*, 48, 131.

TATTAM, C. M., 1929.—The Metamorphic Rocks of North-east Victoria. *Geol. Surv. Vict.*, Bull. 52, 35.

TILLEY, C. E., 1921.—Pre-Cambrian Para-Gneisses of Southern Eyres Pen., S.A. *Geol. Mag. Lond.*, 58, 310.

————, 1925.—Metamorphic Zones in the Southern Highlands of Scotland. *Quart. J. Geol. Soc. Lond.*, 81, 100-112.

————, 1926*a*.—Some Mineralogical Transformations in Crystalline Schists. *Min. Mag. Lond.*, 21, 36.

————, 1926*b*.—On Garnet in Pelitic Contact-zones. Ibid., 21, 47.

————, 1938.—The Status of Hornblende in Low Grade Metamorphic Zone of Green Schists. *Geol. Mag. Lond.*, 75, 499.

TYRRELL, G. W., 1921.—Some Points in Petrographic Nomenclature. Ibid., 58, 501.

VAN HISE, C. R., 1904.—A Treatise on Metamorphism. *U.S. Geol. Surv.*, Mon. 47, 785.

WINCHELL, N. H., and WINCHELL, A. N., 1927.—Elements of Optical Mineralogy. New York, 375.